Quantifying the Toposequential Distribution of Environmental Resources and Its Relationship with Rice Productivity in Rainfed Lowland in Northeast Thailand

（東北タイ天水田地域における環境資源とイネ生産力の地形連鎖分布の量的解析）

2002

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Contents

Introduction

Recent criticisms on the world food security recommended more production of the staple cereals (Evans, 1999; Speth, 1998). Rice which supports most population in Asia is also necessary for rapidly increase of production (IRRI, 1993). As expansion of cultivated area hardly has possibility, the increase of production in rice must be curried out by the increase of productivity. Peng and Senadhira (1998) estimated that the year 2030 target yield was 4.7 t ha^{-1} at lowland ecosystem while the present yield was 2.3 t ha^{-1}. Past increase in rice yield occurred mainly in irrigated land, but the increase rate has been slowing down according to yield leveling for intensive managements (Hossain, 1998). The fact suggests that the improvement of productivity in rainfed rice is quite important and urgent.

Rainfed rice occupied 27 % of total rice culture area all over the world and as much as 45 % of that in Southeast Asia (FAO, 1991). The yield at those areas is generally low because of frequent drought and low soil fertility (Garity et al., 1986; Wade, 1998). Northeast Thailand is a representative rainfed rice producing region of Southeast Asia. The production is characterized by quite low productivity (1.7 t ha^{-1} on average, OAE, 1995) and highly variabile with respect to time and space (Fukui, 1993; KKU-FORD, 1982).

Drought in Northeast Thailand is generally divided into early and late season droughts (Chang et al., 1979). Early season drought is caused by intermittence of precipitation in rainy season, called dry spell, which sometimes continues more than one month (Polthanee, 1996; Fukui, 1993). The dry spell delays rice transplanting otherwise gives rice plants severe damages (Miyagawa, 1996; Kono et al., 2001). Most traditional rice cultivars in the area head out at the terminal period of rainy season (Fukui, 1993).

Water shortage, which happens in the period from the heading to maturity, is called late season drought and recognized as more harmful to rice yield (Fukai et al, 1998; 1999b). Kono (1985) analyzed that farmers obtained plentiful yield without severe drought in only about 4 years out of 10.

Course texture soils occupy 90 % of paddy soils in Northeast Thailand (Panichapong, 1988; Arunin et al., 1994). These soils are generally not fertile and modest in response to applied fertilizer (Ragland et al., 1987; Dudal, 1980). Low organic matter content in soils is also linked with low fertility (Willet, 1995). Kawaguchi and Kyuma (1969) revealed that soil chemical and physical characteristics in Northeast Thailand are extremely ill suited for rice production among Southeast Asia countries.

Geographical features in Northeast Thailand are formed with numerous numbers of small and shallow mini-watersheds, called *Nong* in Thai (KKU-FORD, 1982). Some of these mini-watersheds lead into rivers and others are closed. In area, they are usually only a few square kilometers and some meters in altitude. Paddy fields are found throughout most parts of these mini-watersheds, except for the highest areas, which are used for upland crops, woodland and residences (Miyagawa et al., 1985; Craig and Pisone, 1985). Rice crops grown in lower areas of mini-watersheds sometimes suffer from floods, while those grown in higher areas suffer from drought (Kono et al., 1985; Craig and Pisone, 1985). Soils in higher areas are well known to be, on the whole, less fertile than those in lower areas because of soil erosion and nutrient leaching (KKU-FORD, 1982). Such water and soil conditions imply that rice productivity is highly variable, even within a small area, depending on the topographical positions of the fields.

In order to improve the rainfed rice productivity under such conditions, many studies have been conducted in the areas of crop and land managements and breeding (Ladha et al., 1998; Fukai and Basnayake, 2001).

Chemical fertilizer application, being common in the rainfed rice farming at the present, seems to increase the yield (Pandy, 1998). Other technical changes, such as usages of hand tractor and chemicals, and adoption of direct seeding, are spreading not for the increasing productivity but for the labor saving (Konchan and Kono, 1996; Miyagawa et al., 1999). Incorporation of organic matter was indicated to improve the soil fertility then rice yield (Supapoj et al., 1998; Naklang et al., 1999), but sources of organic matter are very limited. Green manure or relay-cropping of legumes may increase the rice productivity (Carangal and Morris, 1986; Pandey, 1991; Herrera et al., 1997), if their methods are practical.

The breeding strategy in the past in Thailand aimed to shorten growth duration of rice in order to avoid late season drought (Somrith, 1996). Increasing tolerances to drought and low soil fertility are still the major objectives of breeding, and thousands of numbers of lines have been tested (Pantuwan et al., 2001; Jongdee, 2001). Breeding for higher yielding cultivars with shorter statue are also conducted (Somrith, 1996; Cooper et al., 1999). Although these breeding work developed many new varieties, KDML 105 (released in 1959) and RD 6 (released in 1977) (Bunduang and Uchin, 1990), which head out around the terminal period of rainy season, are still planted at a half of paddy fields in Northeast Thailand (Miyagawa et al., 1999).

Consequently, these effects seem scarcely to improve the productivity of rainfed rice in the area. Not only low soil fertility or drought, but also their interaction makes the problem complicate and difficult to solve. Depending on the magnitude of water stress, soil fertility may differently affect rice production (Fukai et al., 1999a). Spatial and yearly variabilities in soil fertility and water availability are also too large and complicated to analyze rice responses to growth conditions in fields. For dealing with the variability of environmental resources in rainfed rice producing areas in Northeast Thailand, analyses based on genotype-by-environment (G × E) interactions have been employed in many studies (Cooper, 1999;Wade et al., 1999c), yet the identified facts are very few.

The review above suggests importance of the research that quantifies spatial and temporal distributions of field water availability and soil fertility, and their relationships with rice productivity, in order to develop more productive and stable rice production technologies in rainfed lowland in Northeast Thailand. This study aims to quantify spatial distributions of soil fertility and water availability in rainfed lowland in Northeast Thailand and how those environmental resources determine rainfed rice productivity, and to identify what producing technology are able to improve the productivity there. For those objectives, some typical mini-watersheds were selected for research area in Ubon Province in Northeast Thailand. In-depth field research on the distribution of the environmental resources was conducted across the toposequence in the mini-watersheds, and its relationship with rice productivity was quantified.

This thesis describes the results of the field investigations and their quantitative analyses in accordance with the objectives. Chapter 1 and 2 describe the results of field investigations on the toposequential variabilities of soil fertility and water availability in farmers' fields in the mini-watersheds. Chapter 3 describes the results of analysis of how and to what extent biomass production of rainfed rice is affected by the distribution of those environmental resources. Effects of farmers' crop and land managements on rice yield were analyzed and the results are presented in Chapter 4. In Chapter 5, the results of the field investigation and data analyses explained in the forgoing chapters were integrated into a simple model to simulate rainfed rice yield in the mini-watersheds as a function of toposequential distribution of soil fertility and crop managements (cultivars, transplanting time and fertilizer application rates). The simulation results under various managements conditions are presented and discussed. On the basis of these analyses, more adaptive production technologies that improve rice productivity in rainfed lowland in Northeast Thailand are proposed in the chapter of general discussion and conclusions.

Acknowledgements

This study could be concluded by supports of so many people. First, I would like to express my deep gratitude to Professor Takeshi Horie of Kyoto University for his guidance during this study. I am also indebted to Mr. Nopporn Supapoj, Director of Ubon Rice Research Center (URRC), Thailand, for his affording every facility for conducting the experiment. Sincere thanks are due to Emeritus Prof. Kazutake Kyuma, Kyoto University, for giving me opportunity to conduct this research, and Emeritus Prof. Yasuo Takai, The University of Tokyo, for his fruitful suggestion on soil organic carbon content. I greatly appreciate Dr. Tatsuya Inamura, Dr. Tatsuhiko Shiraiwa and Mr. Hiroshi Nakagawa of Kyoto University and Dr. Masao Ohnishi of Shimane University for their advice and simulating discussion. I wish to record my appreciation to Dr. Nobuyuki Kabaki and Dr. Naruo Matsumoto of Japan International Research Center for Agricultural Sciences (JIRCAS) who collaborated on soil analysis, and Ms. Suda Sripodok and Ms. Waraporn of URRC who offered me weather data there. Special thanks are due to Prof. Tetsuo Sakuratani, Dr. Toru Matoh, Dr. Eiji Nawata, Dr. Yasuyuki Kono and Mr. Kota Watanabe of Kyoto University, Prof. Shuichi Miyagawa of Gifu University, Dr. Yorthin Konboon and Dr. Grienggrai Pantuwan of URRC and Dr. Sakda Jongkeawwattana of Chiang Mai University, for giving me valuable information about Thai agriculture. I appreciate fruitful discussions with members of Modeling Agricultural Production in Northeast Thailand (MAPNET) project, and also with members of Khon Kaen University, Thailand. I wish to thank Mr. Suksan and the other farmers, who kindly offered me permission to conduct investigation at their fields. Devoted assistance on the experiment of Mr Chamnean Thongthai and Mr. Pitak Sroysin of URRC are greatly appreciated. I am also indebted to Mr. Satoru Yamamoto, Mr. Hiroshi Shibukawa and Mr. Tatsunori Suzuki and other members of Crop Science Laboratory, Kyoto University, for their help in carrying out the experiment. Thanks are also due to villagers of investigated area, members of URRC, and members of Multiple Cropping Center, Chiang Mai University, for their help and friendship. Finally and most importantly, I appreciate Izumi and our soon born baby for their encouragement, and also my parents and my sisters for their support for my studying.

Topographical Variation in Soil Fertility of Rainfed Low-land Paddy Fields in Mini-Watersheds (Nong)

Rice paddy fields in Northeast Thailand extend on numerous complex, small and shallow mini-watersheds called Nong in Thai. Some of those mini-watersheds are opened to river and others are closed, and their undulation is generally a few km in the breadth and a few m in the depth. Rice production there is commonly conducted with rainfed water and the productivity is quite low and unstable. Several studies reported that the low productivity in rice was mainly caused with drought and low soil fertility (Fukai et al., 1998; Wade et al., 1999b).

It is reported that topographical difference in field position in mini-watersheds gives differences in water availability and soil fertility (Miyagawa and Kuroda, 1988; Wade et al., 1999b). Generally, rice fields at upper parts of mini-watersheds are quite poor in water availability and soil fertility, while those at lower parts are rich. Such a large field-to-field difference in environmental resources will be a principal problem, when new variety and crop management are introduced there for improvement of rice productivity. However, quantitative information about the topo-sequential variability is scarce.

Many studies suggested that low fertile soils in Northeast Thailand are generally linked with coarse texture and poor organic matter content ([illegible], 1980; Willet, 1995). The soil series map of Department of Land Development, Thailand, proposes a few dozens of soil series classifications depending on geography and soil materials as defined in Moormann et al. [illegible]. It is useful for [illegible] soil management and fertilization plans, but it seems that paddy fields belonging to a same soil series have highly different rice productivity. Therefore, it is important to quantitatively

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Many studies suggested that low fertile soils in Northeast Thailand were generally linked with course texture and poor organic matter content (Dudal, 1980; Willet, 1995). The soil series map of Department of Land Development, Thailand, provides a few dozens of soil series classifications depending on geography and soil characters as defined in Moormann et al. (1964). It is useful for checking soil characteristics and distribution roughly, but it seems that paddy fields belonging to a same soil series have largely different rice productivity. Therefore, it is important to quantitatively evaluate and analyze soil fertility in relation to toposequence in mini-watersheds as a basis for more productive and stable rice production technologies in rainfed rice culture in Northeast Thailand. For that purpose, we collected soil samples from farmers' fields located at different toposequential positions within four mini-watersheds in Northeast Thailand, and investigated fertility of the collected soils by phytometer experiment with potted rice as test plant. This chapter describes toposequential distributions of soil fertility and rice productivity, and major soil factors associated with them in rainfed lowland paddy fields in mini-watersheds in Northeast Thailand.

Materials and method

1. Research site and soil sampling

Soils used in this study were collected from a rainfed rice culture area located at about 25 km northwest from the center of Ubon Ratchathani City; the area extends along Se Bai River, a branch of Moon River. Four mini-watersheds were selected in the area as research sites as shown in Fig. 1.1. Each site consisted of traverse lines at each mini-watershed (*Nong*). Mini-watersheds of Wang O and Kha Khom sites are opened to rivers, and those of Hua Don and Mak Phrik are closed. The traverse lines of Wang O and Mak Phrik were from top fields to bottom fields of the mini-watersheds, and those of Kha Khom and Hua Don extended from top field on one side through bottom fields to the top on opposite side in mini-watershed. The lines of Wang O, Kha Khom, Hua Don and Mak Phrik site were about 200, 500, 350 and 150 m in the length and 6.0, 1.5, 3.4 and 2.6 m in the difference in relative field elevation, respectively. The width of Hua Don site was 250 m and widest, and those of the others were about 50 m. Soils in Wang O site are classified to Khorat series according to soil map published by Department of

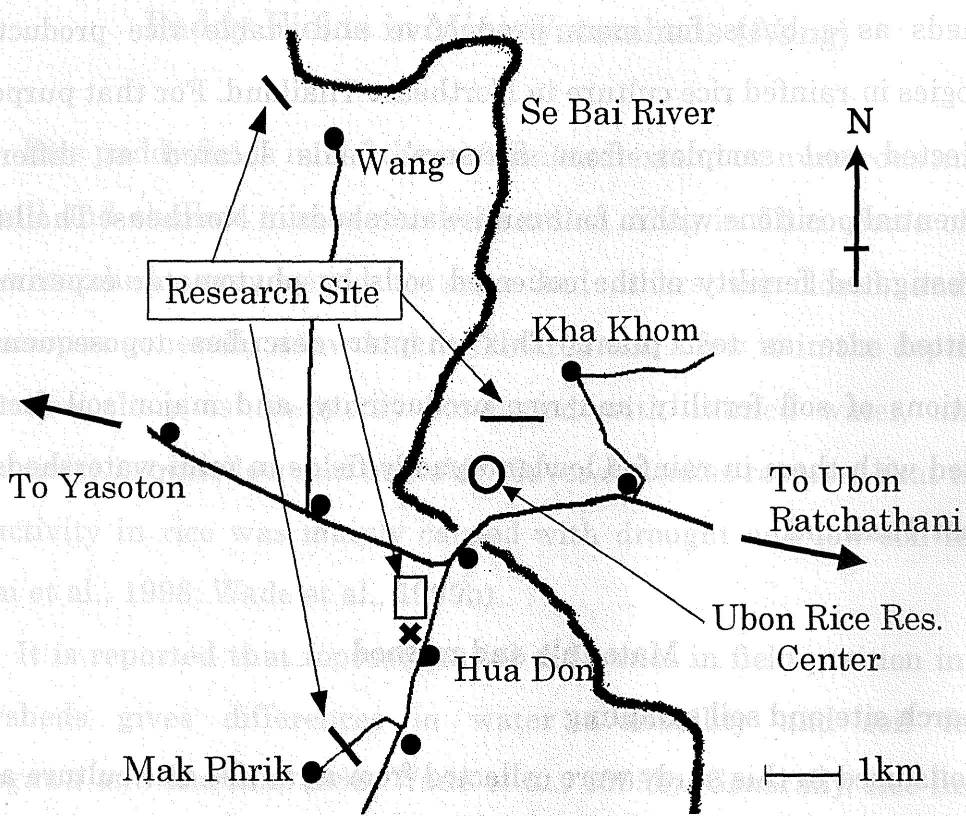


Fig. 1. 1. Map of research sites. ● shows village and ✖ the secondary-grown woodland where soil samples were collected.

Land Development, Thailand (Changprai et al., 1971), and those in Kha Khom, Hua Don and Mak Phrik are classified to Ubon and Khorat, Pimai and Ubon, and Roi Et series, respectively.

Plow layer soils (20 cm in depth) were sampled from 5 different paddy fields at Wang O site and 7, 31 and 5 fields at Kha Khom, Hua Don and Mak Phrik site, respectively. These fields were belonging to one farmer at Wang O site, and six, five and one farmer at Kha Khom, Hua Don and Mak Phrik site, respectively. Toposequential positions of the paddy fields were presented with the field elevation relative to the lowest paddy field in each site. Surface soils from 2 spots at secondary-grown woodland adjacent to Hua Don site (Fig. 1.1) were also collected. The relative elevations of the spots were 3.9

and 4.0 m on the basis of Hua Don site. Soil sampling was done after first plowing in June 1998. Sampled soils were air-dried, cracked, passed through 1 mm-mesh sieves to remove plant residues. Soil organic carbon (SOC) content was measured for each soil by Walkly and Black method (Walkly and Black, 1934), and soil texture was measured by pipette method.

2. Phytometer experiment

Phytometer experiment with rice as test plant was conducted for evaluation of soil fertility. The 50 soil samples as described above were filled in pots, which were 7.0 L in sizes and contained 5.5 kg dry soils, then used for rice culture without fertilizer application. In addition to this, soil samples from representative 10 fields at Hua Don site were also used for rice culture at different fertilizer treatments. The fertilizer treatments consisted of N-P_2O_5-K_2O applications of 0-0-0 (None), 0.6-0-0 (N), 0.6-0.6-0 (NP), 0.6-0-0.6 (NK) and 0.6-0.6-0.6 g pot^{-1} (NPK). Three pots were used for each soil and each treatment as replications. Three seedlings of rice cultivar KDML105 were transplanted on each pot on 30 July 1998 and grown under flooded condition till the maturity at 13 November. Then plants were harvested and subjected for determination of dry weight and nitrogen (N) content. The N content was determined by near infrared spectroscopic analysis method (BRAN + LUEBBE, Infra Analyzer 500) equipped with IDAS software, calibrated with Kjeldahl method.

Results

1. Variation in soil fertility and the associated factors

Dry matter production of rice grown in pots without fertilizer application differed as large as more than 5 times among soils from different fields. Soil organic carbon (SOC) content had a close correlation with the dry

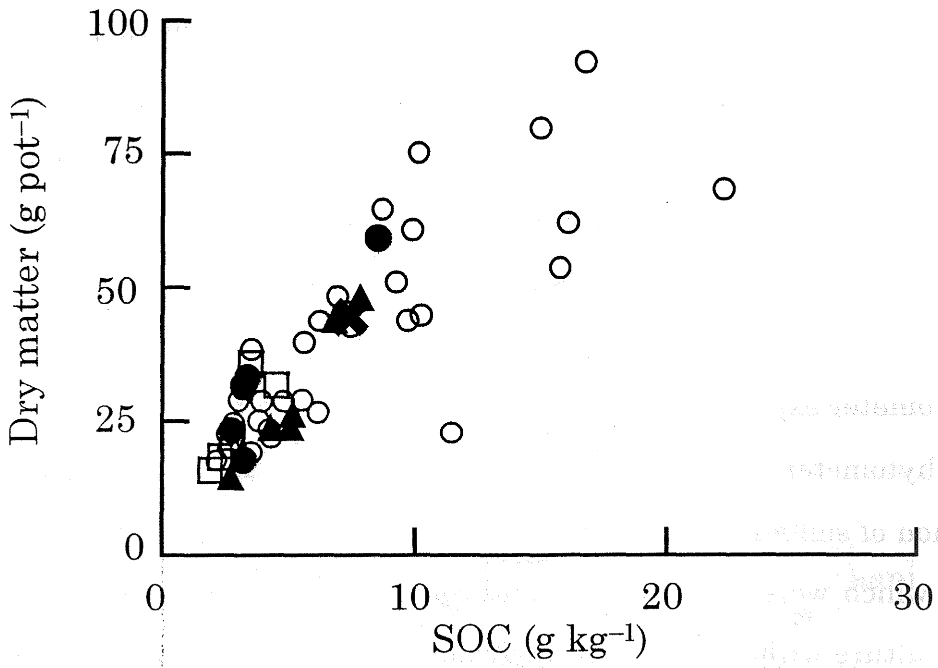


Fig. 1. 2. Relation between soil organic carbon (SOC) content and rice dry matter production at maturity under unfertilized condition. Soils were sampled from Wang O (□), Kha Khom (▲), Hua Don (○) and Mak Phrik site (●). ✖ shows the data point for soils from a secondary-grown woodland adjacent to Hua Don research site.

matter production (Fig. 1.2, r = 0.81, P < 0.01), while clay content did comparatively smaller correlation with that (r = 0.48, P < 0.01). The result suggests that SOC content is a good index for soil fertility in terms of rice dry matter production, regardless of the difference in sites and fields or woodland.

Although physiological efficiency of nitrogen (N) for dry matter production was slightly higher under unfertilized (173 g g^{-1}) than under NPK fertilized conditions (149 g g^{-1}), the dry matter production was proportional to plant N uptake under both conditions (Fig. 1.3). The N uptake in rice significantly increased by N fertilization (P < 0.01, Table 1.1). Under N fertilized condition, phosphorus (P) fertilizer significantly increased plant N uptake (P < 0.01), but effect of potassium (K) fertilizer gave insignificant

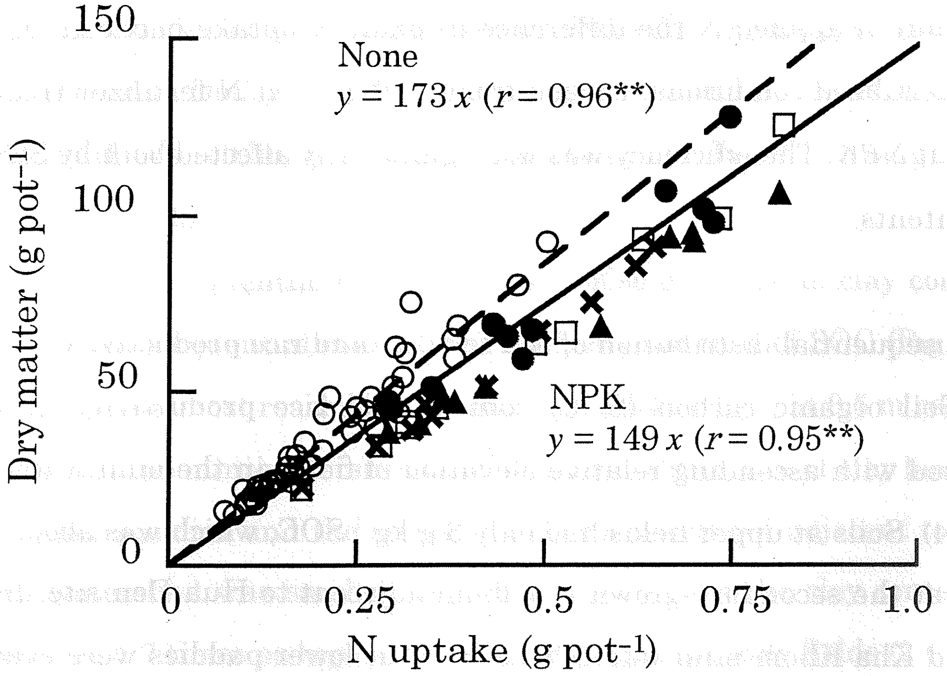


Fig. 1. 3. The response in rice dry matter to nitrogen (N) uptake at maturity as measured by pot growth experiment. ○ None, ✖ N, ▲ NP, □ NK and ● NPK fertilizer treatment.

Table 1.1. Plant nitrogen (N) uptake and fertilizer N recovery rate under different fertilizer treatment in pot-grown rice.

Fertilizer treatment	N uptake	N recovery rate
None	0.24 ± 0.12 [a]	
N	0.42 ± 0.16 [b]	0.30 ± 0.12 [a]
NP	0.52 ± 0.19 [c]	0.47 ± 0.12 [b]
NK	0.47 ± 0.21 [b]	0.37 ± 0.16 [a]
NPK	0.53 ± 0.17 [c]	0.48 ± 0.13 [b]

Average ± standard deviation. n = 10. Values on a column followed by the same letter are not significantly different at 5 % level.

effect on it. The fertilizer N recovery rate, which was calculated by dividing by amount of applied N the difference in plant N uptake between fertilized and unfertilized conditions, ranged from 0.30 g g^{-1} at N fertilizer treatment to 0.48 at NPK. The efficiency was not significantly affected both by SOC and clay contents.

2. Toposequential distribution of soil fertility and rice productivity

Soil organic carbon (SOC) content and rice productivity generally decreased with ascending relative elevation of fields in the mini-watersheds (Fig. 1.4). Soils at upper fields had only 3 g kg^{-1} SOC, which was about a half of that at the secondary-grown woodland adjacent to Hua Don site. In Hua Don and Kha Khom mini-watersheds, SOC at lower paddies were evidently much more than that at the upper, and at Hua Don site it exceeded 10 g kg^{-1}. However, such an increase of SOC at lower fields was not observed in Wang O site. These toposequential distributions of SOC caused the variation in rice

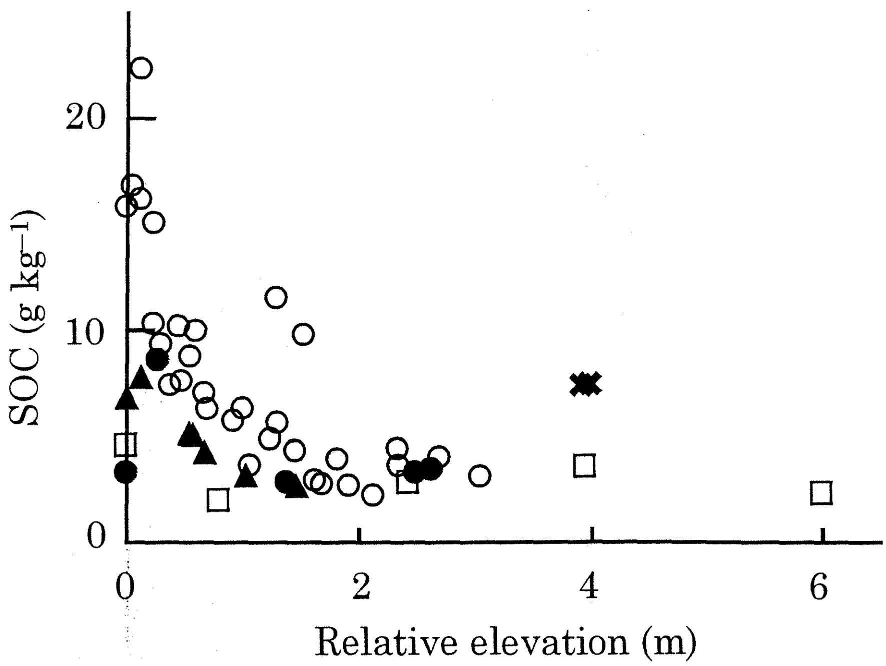


Fig. 1. 4. Soil organic carbon (SOC) content as a function of the relative elevation of farmers' fields in mini-watersheds. Symbols are the same in Fig. 1.2.

dry matter production as determined by the phytometer experiment. The dry matter production was closely negatively correlated to the relative elevation of fields in the Hua Don ($r = -0.72$, $P < 0.01$), Kha Khom ($r = -0.91$, $P < 0.01$) and Mak Phrik ($r = -0.56$) mini-watersheds, but the relation at Wang O was not clear ($r = -0.10$).

Such a toposequential distribution was also observed in clay content. However, its toposequential change was steeper than that of SOC (Fig. 1.5). The clay content almost reached the minimum, 0.04 kg kg^{-1}, at 0.5 m relative elevation in all the mini-watersheds. Although the difference of clay between soils at upper paddies and the secondary-grown woodland adjacent to Hua Don mini-watershed was smaller than that of SOC, yet the clay content at woodland was 1.7 times as high as those at uppermost paddy fields (2 to 3 m) in Hua Don site. This suggests that clay has eroded in many years of rice farming after deforestation.

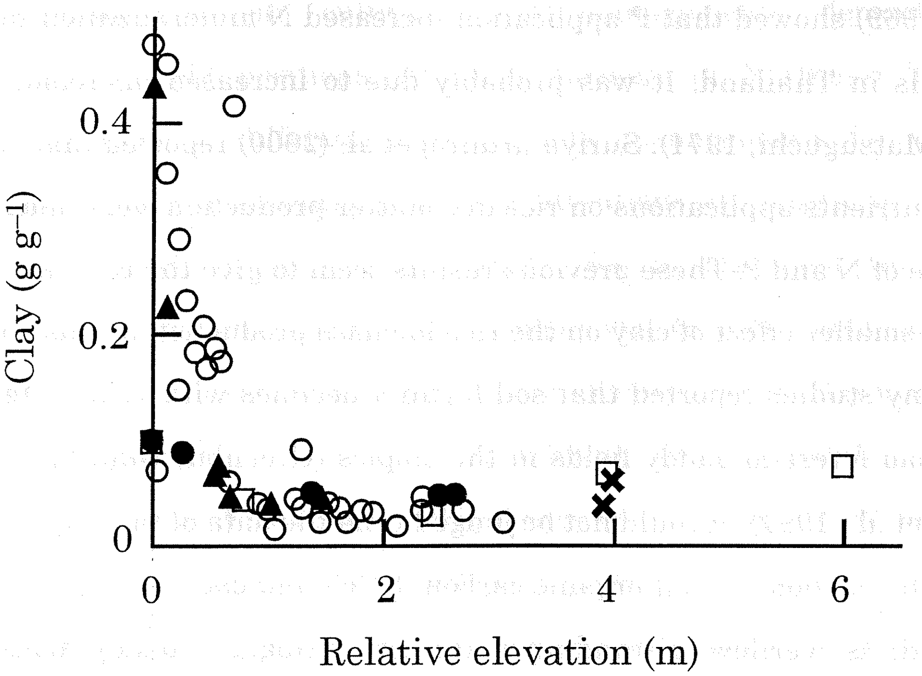


Fig. 1. 5. Clay content as a function of the relative elevation of farmers' fields in mini-watersheds. Symbols are the same in Fig. 1.2.

Discussion

The phytometer experiment using rice as test plant indicated that soil organic carbon (SOC) content had much closer relation to rice productivity under unfertilized condition than clay content. The soil fertility generally decreased with ascending relative field elevation in mini-watersheds. Since dry matter production in rice was severely restricted with nitrogen (N) uptake (Fig. 1.2; also Ohnishi et al., 1999b), it was considered that SOC was especially important as a source of N in poor fertile soil there. Willett (1995) indicated that organic matter was also important for increasing cation exchange capacity (CEC), being more effective than clay in the case of sandy soils in Northeast Thailand. This supports the result of the present study.

Application of phosphorus (P) fertilizer significantly increased nitrogen (N) uptake and, as a consequence, rice dry matter production. Several studies indicated such an effect of P fertilizer under N fertilized condition (Ragland et al., 1987; Suriya-arunroj et al., 2000). Kawaguch and Kyuma (1969) showed that P application increased N mineralization rate in paddy soils in Thailand. It was probably due to increased microbiological activity (Matsuguchi, 1971). Suriya-arunroj et al. (2000) reported that effects of other nutrients applications on rice dry matter production were much less than those of N and P. These previous results seem to give the reason for the relatively smaller effect of clay on the rice biomass production in this study.

Many studies reported that soil fertility declines with years after the change from forest to paddy fields in the tropics (Greenland and Lal, 1977; Oldeman et al., 1991). It could not be judged from the data of this experiment whether the erosions of soil organic carbon (SOC) and clay were going on or terminated. As overflow of standing water across ridges of paddy fields was scarcely observed even under heavy rain and clay content almost reached the minimum in most fields except at the bottom of mini-watersheds, the erosion of clay was likely to terminate. Contrary to clay, SOC content may change more dynamically with organic matter input and its decomposition. Since SOC decomposition rate is influenced by clay and moisture contents in soil, the toposequential distribution of SOC content could have been influenced by both the distributions of clay and soil moisture in dry seasons. Under the condition where rice residue is the only source for field organic matter in Northeast Thailand except for a little farmyard manure, the SOC distribution is also reflecting rice productivity for long years. Previous studies showed that more fertile soil was created with rice straw incorporation than without (Chairoj et al., 1996; Naklang et al., 1999). Rice straw management after harvest is one of the key factors for production sustainability. From the same reason, introduction of a semi-dwarf high yielding cultivar, which produces fewer residues with higher harvest index, may reduce sustainability of rice production in this area.

Large field-to field variability in rice productivity as shown in Fig. 1.2 may request different cultivars and managements depending on toposequential field positions. Although farmers in Northeast Thailand sometimes adapted different cultivars and managements for different toposequence in a mini-watershed, their attentions are mostly to standing water and precipitation (Fukui, 1993). As is discussed above, the toposequential gradient in SOC content alone causes enormously large field to field difference in rice productivity, without water stress. However, water status is undoubtedly one of major constraints as in drought, and there exists a close interacting effect of between water availability and SOC content on nutrient availability (Wade et al., 1998). Therefore, investigation on toposequential distribution of water availability and its relation to soil fertility seems necessary for in depth understanding of toposequential distribution of rice productivity in mini-watersheds in Northeast Thailand.

Summary

Mini-watersheds called *Nong* in Thai are geographical components of rainfed lowland rice culture in Northeast Thailand, and constitute distinct units in understanding environmental constraints for low and unstable rainfed rice production there. This study aimed to clarify toposequential variation of soil fertility and rice productivity within mini-watersheds. Phytometer experiment with potted rice using soils sampled from various fields within mini-watersheds, revealed that soil fertility as determined by rice biomass productivity was different as large as 5 times among fields, and that the soil fertility was well represented by soil organic carbon (SOC) contents. The effect of SOC on rice productivity was much larger than that of clay. Over all soils investigated, nitrogen (N) fertilizer was the most effective component to the rice biomass production and phosphorus followed. Toposequential distributions of SOC and clay contents indicated their losses at upper paddy fields with years after deforestation and accumulation at the lower. Reflecting this, soil fertility and rice productivity generally decreased with ascending relative field elevation in mini-watersheds. The result suggests that organic matter management is primarily important for sustainable rice production in this area.

Keywords: clay; erosion; nitrogen uptake; soil fertility; soil organic carbon;

Toposequential Variation in the Delay of Heading as a Water Stress Index of Rainfed Rice in Mini-Watersheds (*Nong*)

Rainfed rice occupied 27 % of total rice culture area in the world and as much as 45 % of that in Southeast Asia (FAO, 1991). Drought is often recognized as the primal constraints for rainfed rice production (Hanson et al., 1990; Garity et al., 1986). Also in Northeast Thailand, one of the representative rainfed rice-producing regions, drought was reported frequently because of the least and unreliable precipitation (Pushpavesa, et al., 1986). Since sufficient water supply with irrigation is rarely possible in this region (Panichapong, 1988), the drought problem still remains for the present.

Geographic feature of Northeast Thailand is represented by numerous numbers of small and shallow mini-watersheds called *Nong* in Thai, which have dimensions of a few km^2 in area and a few m in depth (KKU-FORD, 1982). Paddy fields extend on these mini-watersheds, and water availability at fields generally varies with the toposequential position within mini-watersheds. The toposequential variation in water availability has not been quantitatively described, but only with literary as classifying upper paddy fields into drought-prone and lower into favorable or submergence-prone (Miyagawa et al., 1985; Craig and Pisone, 1988; Wade et al., 1999b). Such a toposequential difference in water availability would inevitably cause a difference in rice production. However, rice productivity is also strongly affected by toposequential variation in soil fertility in the region (Chapter 1), which makes the effect of water stress undistinguishable.

Rice phenological development which is clearly determined by day length and temperature under no water stress conditions shows delay when plants receive water stress. The effect of drought on the phenological development is generally larger than that of nutritional condition (Nakagawa and Horie, 1996; Fukai 1999; Prasertsak and Fukai, 1997; Wonprasaid et al., 1996; Tsuda, 1986). It is generally recognized that the delay of heading is proportional to cumulative water stress (Tsuda and Takami, 1991). The two cultivars of KDML 105 and RD 6, which are the most popular cultivars in Northeast Thailand (Miyagawa et al., 1999), have almost same developmental characteristics (Bunduang and Uchin, 1990), and head out at almost same days when they are seeded from May to mid-August and grown under no water stress conditions, due to their strong photoperiod sensitivity (Ohnishi et al., 1999a; also see Chapter 4 and 5). These facts suggest that heading date of the two cultivars provides a good index of the degree of water stress under custom crop managements of farmers.

Since breeding effort for rainfed lowland rice have paid much attention to drought resistance (Fukai et al., 1999b; Somrith, 1996; Sarkarung and Pantuwan, 1999), information about the degree of water stress and its toposequential variability is valuable for cultivar developments and also for introduction of new cultivars into farmers' fields. The objectives of this chapter is to describe toposequential distribution of water availability and its effect on rice heading dates in rainfed lowland in mini-watersheds in Northeast Thailand. The degree of water stress and its effect of rice yield are also discussed.

Materials and method

Four mini-watersheds, Wang O, Kha Khom, Hua Don and Mak Phrik, were selected for this measurement, which are located in an area at about 25 km northwest from the center of Ubon Ratchathani City; the research area extends along Se Bai River, a branch of Moon River. Mini-watersheds of

Wang O and Kha Khom sites were opened to rivers, and those of Hua Don and Mak Phrik were closed. Field water conditions during rice growth seasons were measured for Hua Don site in 1997 and all four sites in 1998. In 1997, water depth above soil surface and soil moisture content were measured for 6 paddy fields in Hua Don site as denoted in Fig. 2.1. Fig. 2.1 also denotes 10 fields where soil moisture contents were measured in 1998. Measurements of water depth in 1998 were conducted for 247, 5, 7, 5 fields in

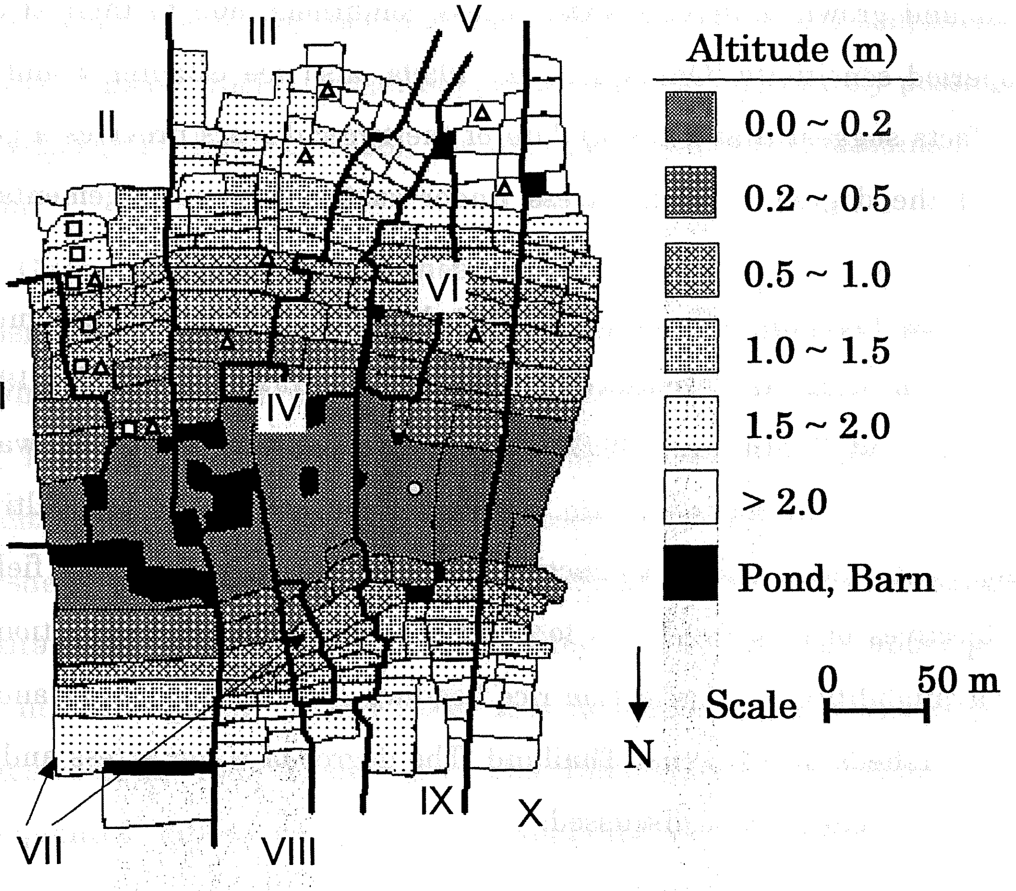


Fig. 2. 1. Map of investigated fields and their elevations relative to the lowest point (o) in Hua Don mini-watershed, Northeast Thailand. 6 fields denoted with (□) had measurement of soil moisture content and water depth above soil surface in 1997. In 1998, soil moisture content was measured at 10 fields denoted with (△) and water depth was measured at all 247 fields.
━ : boundaries between farmers I to X; — : boundaries between fields.

Hua Don, Wang O, Kha Khom and Mak Phrik sites, respectively. The total area of the field measurements in Hua Don covered 9.3 ha belonging to 10 farmers, in which the elevation of the highest paddy field relative to the lowest was 3.4 m (Fig. 2.1). The measured paddy fields at Wang O, Kha Khom and Mak Phrik were selected on traverse lines along the slope of mini-watersheds. The traverse lines of Wang O, Kha Khom and Mak Phrik sites were about 200, 500 and 150 m in the length and 6.0, 1.5 and 2.6 m in the difference in the relative field elevation, respectively. Thus, the toposequential positions of paddy fields were presented with the field elevation relative to the lowest paddy fields in the respective sites.

Water depth above soil surface was measured about one week interval from July to November in 1997 and 1998. The water depth was represented as average of four measurements at different points in each field. Daily water depth was calculated by linear interpolation between two adjacent measurements, and days with water depth above 5 mm were counted for numbers of flooded days. Volumetric soil moisture content was measured twice a week from the end of August to harvest in 1997 and mid-September to harvest in 1998 by time domain reflectometory (TDR) method (Sony Techtronics 1502B) according to the procedure by Topp et al. (1980). In each measurement spot of each field, TDR proves with 20, 50 and 100 cm-length were used in 1997, and those with 20 and 50 cm-length in 1998. These probes were vertically inserted into soil at 2 spots at each field. All the fields of measurements were under rainfed conditions throughout the whole growth periods, except for pumping irrigation at transplanting time in some fields.

Besides these measurements, dates of seeding or transplanting and heading of rice for all the fields were monitored and recorded. Direct seeding at fields and seeding at nursery bed was conducted from May to July. At all the monitored fields either cultivars KDML 105 or its glutinous mutant, RD

6, was grown. Precipitation data was collected at Ubon Rice Research Center, which was located within study area.

Results

Precipitation in 1997 and 1998 were shown in Fig. 2.2. The amounts, 1114 and 1186 mm, were much less than the normal (1506 mm, 1987 – 1996 averages) but not so rare (1260 mm in 1988 and 1214 mm in 1993). Rainy season started in May and ended in mid-October in both years as in ordinary years. Durations of rain intermissions in rainy seasons, so called dry-spell,

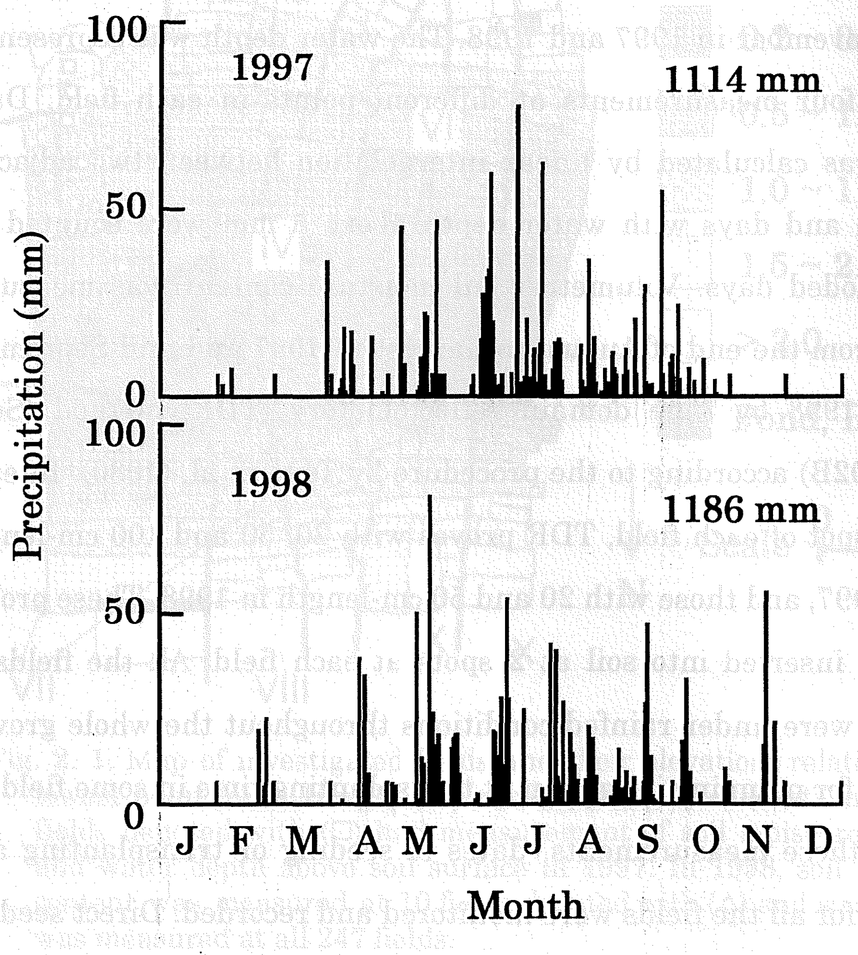


Fig. 2. 2. The precipitation at Ubon Rice Research Center, Northeast Thailand 1997 and 1998.

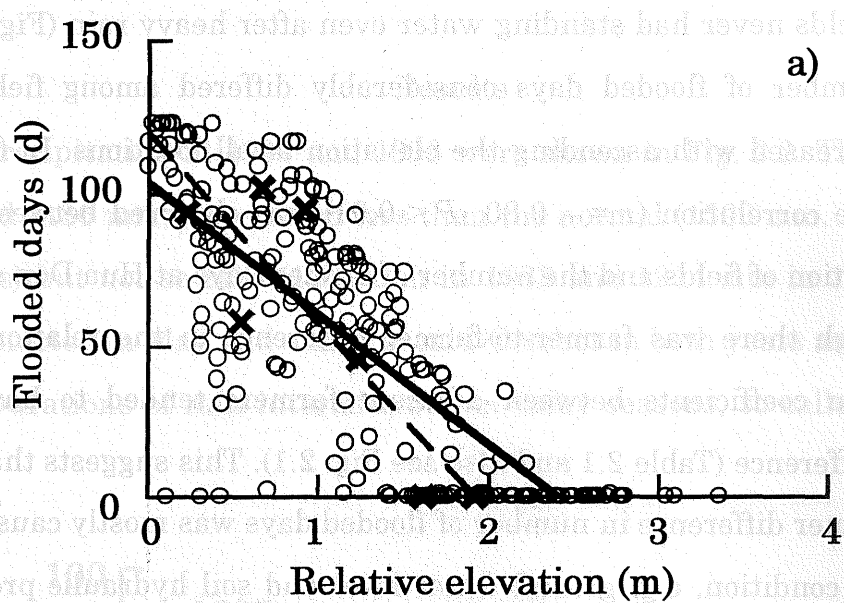
were not longer than 2 weeks in both years. In spite of such a dry spell, fields at bottom of mini-watersheds always had standing water. Contrarily, uppermost fields never had standing water even after heavy rain (Fig. 2.3). Although number of flooded days considerably differed among fields, it generally decreased with ascending the elevation at all locations. In fact, a close negative correlation ($r = -0.80$, $P < 0.01$) was observed between the relative elevation of fields and the number of flooded days at Hua Don site in 1998. Although there was farmer-to-farmer difference in the relationship, the regression coefficients between adjacent farmers tended to have no significant difference (Table 2.1 and also see Fig. 2.1). This suggests that the farmer-to-farmer difference in number of flooded days was mostly caused by underground condition, e.g. ground water level and soil hydraulic profiles, and less by farmers management. On average over all fields at Hua Don in 1997 and at four research sites in 1998, number of days that fields had standing water was approximately half of rainy season duration.

Table 2. 1. Difference among farmers in the linear regression relationship of field flooded days to relative elevation at Hua Don mini-watershed in 1998.

Farmer	n	regression [a]				r [b]
I	10	y =	− 100.8 x +	134.3	a	0.96**
II	20	y =	− 57.1 x +	112.2	b	0.89**
III	64	y =	− 35.4 x +	81.3	c	0.68**
IV	2					
V	23	y =	− 33.7 x +	90.0	cd	0.74**
VI	14	y =	− 57.6 x +	132.4	de	0.86**
VII	12	y =	− 50.6 x +	121.8	b de	0.78**
VIII	16	y =	− 63.2 x +	124.3	b	0.95**
IX	46	y =	− 43.7 x +	111.5	de	0.87**
X	40	y =	− 41.1 x +	112.8	e	0.94**
Total	247	y =	− 42.8 x +	103.4		0.80**

[a] followed by a common letter are not significantly different at 5 % level.

[b] ** significance at 1 % level.



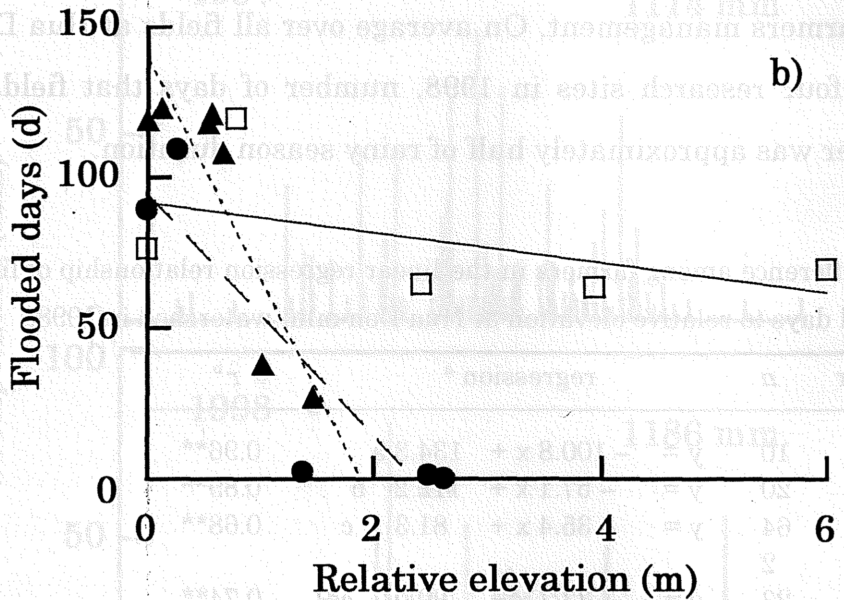


Fig. 2. 3. Number of flooded days as a function of relative field elevation of farm fields at mini-watersheds in Northeast Thailand wet season (1 July – 31 October). (a) at Hua Don mini-watershed in 1997 (✖, broken line) and 1998 (○, solid). (b) at Wang O (□, solid), Kha Khom (▲, dotted), and Mak Phrik (●, broken) mini-watershed in 1998.

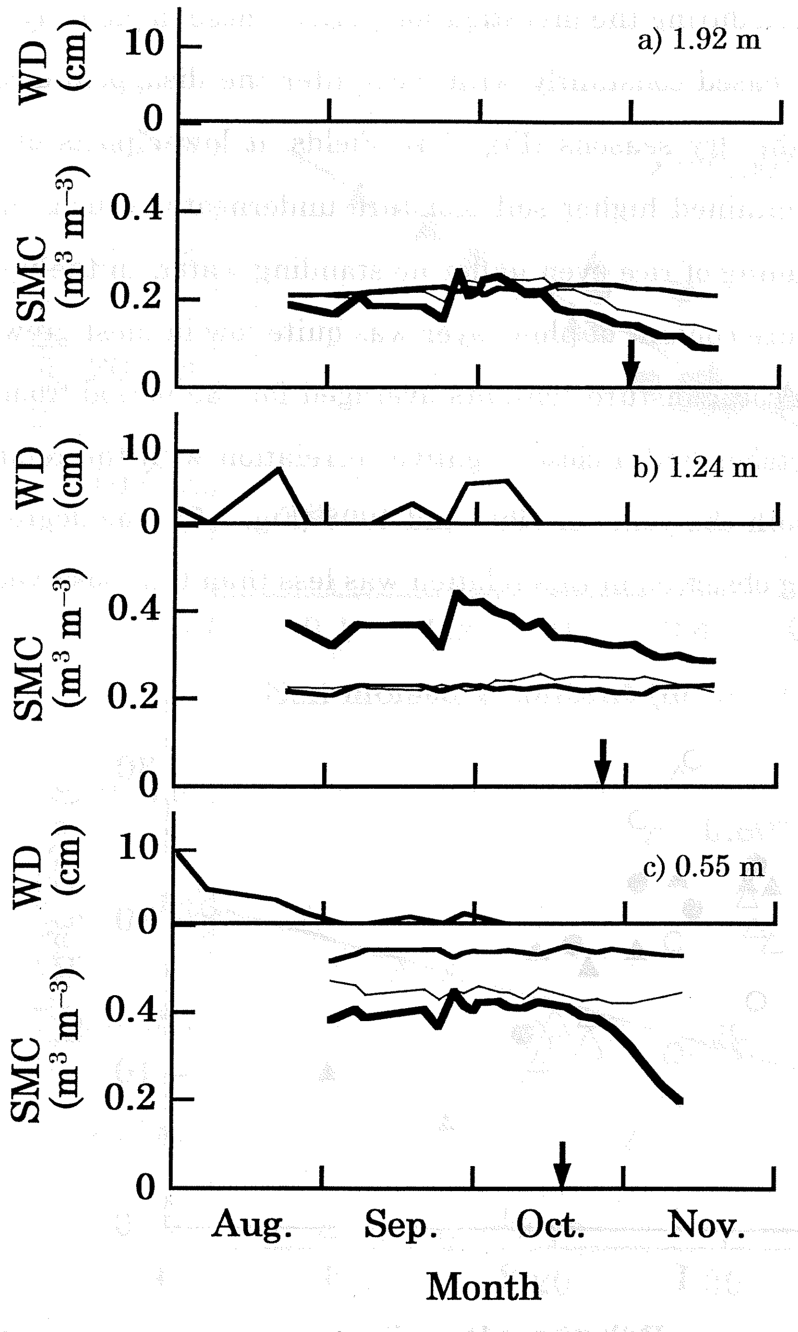


Fig. 2. 4. Time course of standing water depth and soil moisture content at fields of different elevations at Hua Don mini-watershed in 1997. Values on the figure show relative elevation of the fields. ▬ , —— , and —— show soil moisture contents averaged for depth of 0 ~ 20, 20 ~ 50 and 50 ~ 100 cm, respectively. Arrows show heading days in rice.

While volumetric soil moisture content in deep layer soil (50 ~ 100cm depth) hardly changed during the investigation period, those in plow layer (0 ~ 20 cm depth) decreased constantly with days after the disappearance of standing water in the dry seasons (Fig. 2.4). Fields at lower parts of the mini-watershed maintained higher soil moisture underneath, which didn't decrease till the heading of rice even under no standing water. In the upper fields the soil moisture content of plow layer was quite low in most growing seasons. Plow-layer soil moisture contents averaged for the period from 15 September to 15 October had a close negative correlation with the relative field elevation for both the years of 1997 and 1998 (Fig. 2.5). The degree of data point scattering observed in this relation was less than that observed in

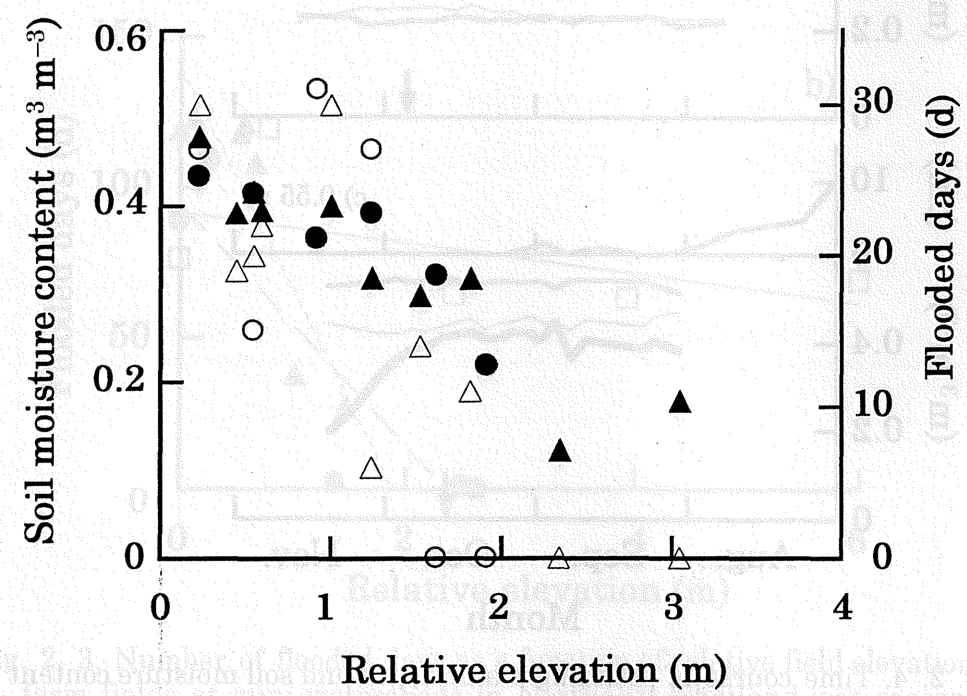


Fig. 2. 5. Plow-layer (0 ~ 20 cm) soil moisture content averaged for the period from 15 September to 15 October (●, ▲) and number of flooded days for the period (O, △) as a function of relative elevation of farm fields at Hua Don mini-watershed in 1997 (circle) and 1998 (triangle).

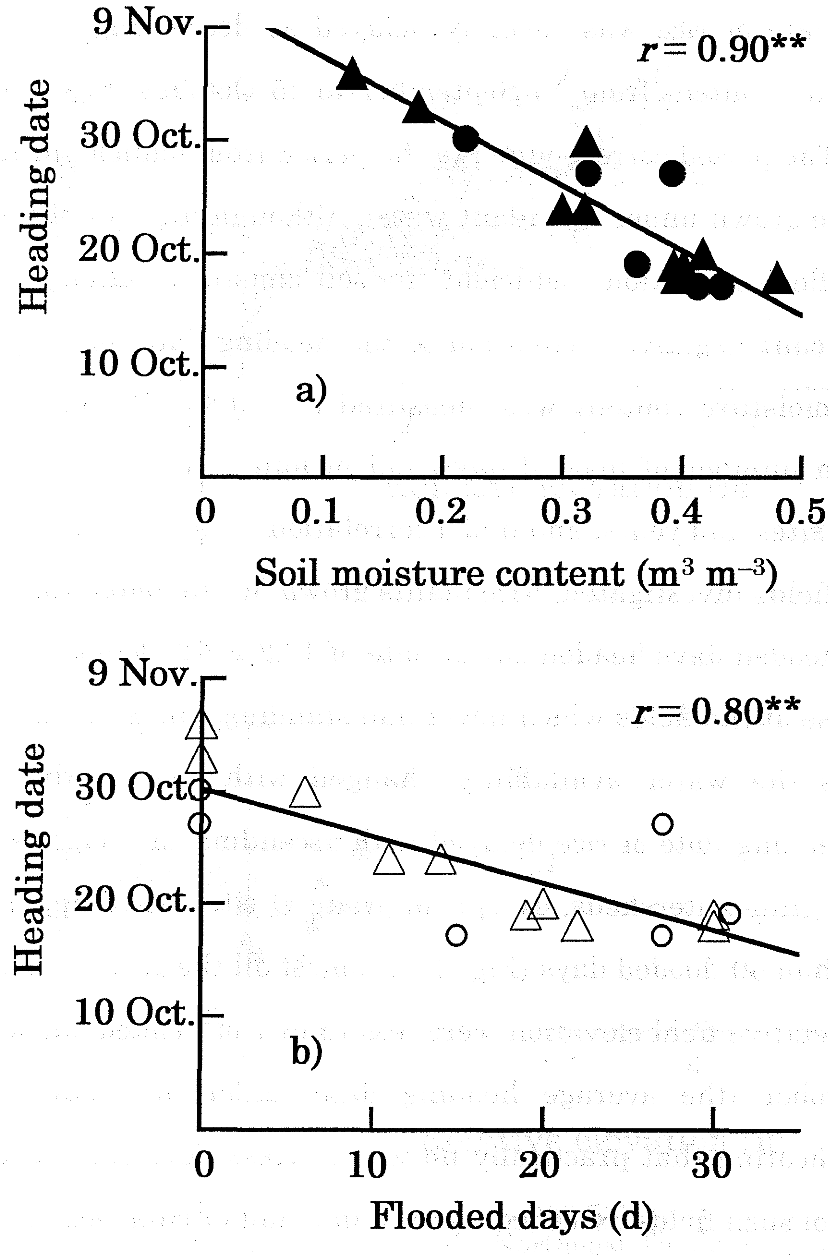


Fig. 2. 6. Heading date in rice as functions of soil moisture content (a) and flooded days (b) for farmers' fields in Hua Don mini-watershed. Soil moisture content and flooded days were measured from 15 September to 15 October. Symbols are the same in Fig. 2.5.

the relation between the number of flooded days and relative elevation, which emphasizes that water availability is definitely determined with the relative field elevation.

Heading date of rice was severely delayed as decreasing the plow-layer soil moisture content from 15 September to 15 October (Fig. 2.6; r = 0.90, $P < 0.01$). The period corresponded to the period from panicle initiation to heading of rice grown under abundant water. Although number of flooded days had a smaller correlation coefficient the soil moisture content, it also showed a significant negative correlation to the heading date for the fields where the soil moisture content was measured (r = 0.80, $P < 0.01$). The relation between number of flooded days and heading date of rice wasn't different among sites and years, and had a correlation coefficient of 0.75 ($P <$ 0.01) for all the fields investigated. Rice plants grown at the fields which had more than 100 flooded days headed out at date of 17.2 ± 2.2 October in both years, while those at the fields which never had standing water did at 28.9 ± 4.9 October. As the water availability changed with the relative field elevation, the heading date of rice delayed with ascending the relative field elevation in the mini-watersheds, except for Wang O site where uppermost field had more than 60 flooded days (Fig. 2.7). Almost all the rice crops at the fields of which relative field elevation were less than 1 m headed out within 17.2 ± 2.2 October (the average heading date under abundant water availability), indicating that practically no water stress developed in those fields. The area of such fields exceeded more than a half of Hua Don site (see Fig. 2.1). On the contrary, droughty fields located at upper parts of Hua Don, Kha Khom and Mak Phrik sites, where rice heading dates delayed more than 10 days.

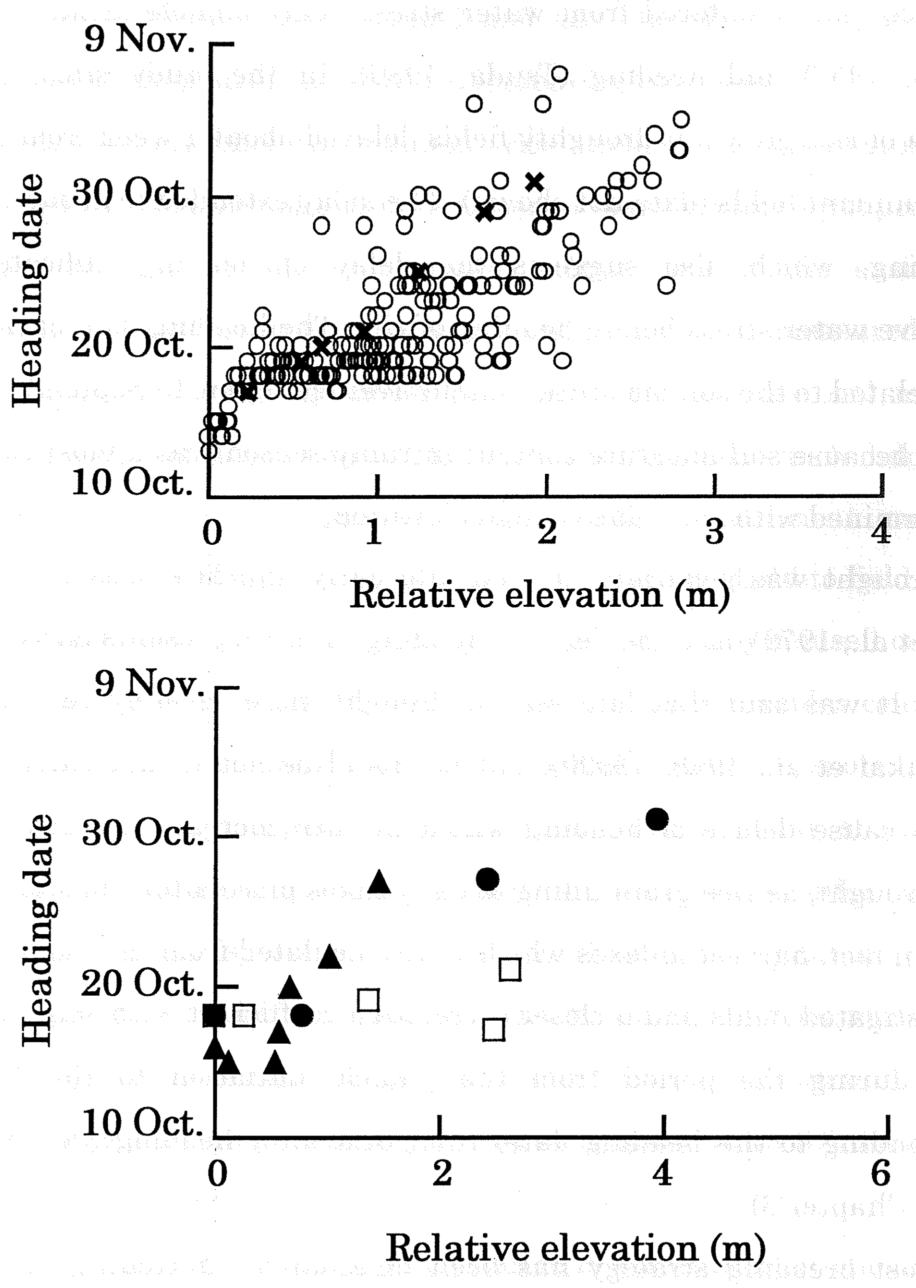


Fig. 2. 7. Relationship between heading date in rice and relative field elevation in mini-watersheds, Northeast Thailand. (a) at Hua Don mini-watershed. (b) at Wang O, Kha Khom and Mak Phrik mini-watersheds. Symbols are the same in Fig. 2.3.

Discussion

Rice plants suffered from water stress delay panicle initiation (Oka and Rao, 1957) and heading (Tsuda, 1986). In the study sites, panicle initiation of rice grown at droughty fields delayed about 1 week from that at water abundant fields (data not shown). The delay extended to about 10 days at heading, which also suggests the delay of heading indicates the cumulative water stress before heading of rice. The heading date of rice was closely related to the soil moisture content averaged from 15 September to 15 October, because soil moisture content in rainy season was almost constant and determined with the relative field elevation.

Drought was generally divided into early and late season droughts (Chang et al., 1979), and the delay of heading of rice represents early season drought. It was said that late season drought more severely reduced rice yield (Fukai et al., 1998; 1999b), but it should be noted that early season droughts cause delays of heading which in turn increase severity of late season drought, as rice grain filling usually takes place after the start of dry season. In fact, harvest indexes which were calculated from the yield data at the investigated fields had a closer correlation coefficient with soil moisture content during the period from the panicle initiation to the heading (corresponding to the heading date) than that after heading (described in detail in Chapter 3).

Most breeding strategy has been directed to shortening of growth duration of rice in order to avoid late season drought (Somrith, 1996; Fukai et al., 1999b). In such droughty fields as those located in upper parts of Hua Don site, breeding of genotypes with earlier heading may help reduce drought damages. The earlier heading means shorter growth duration and sometimes brings a reduction of rice yield under the extremely low soil fertility as in Northeast Thailand (Tirol-Padre et al., 1996; Cooper. 1999).

Rice paddy fields are necessarily classified according to water availability when a new cultivar is introduced, and the classification may also be beneficial to develop strategies toward increasing rice yield.

Water availability in rainfed rice fields has frequently been represented by existence of standing water in many studies (Wonprasaid et al., 1996; Sharma et al., 1995. Fukui, 1993), due to the easiness of measurement. However, the water stress effect on rice as measured by the delay of heading had much closer relation to the average soil moisture content than that of flooded days. There were some fields which didn't have much standing water despite their soils having sufficient moisture. Existence of such fields suggests that horizontal field-to-field water movement occurred such as a seepage through ridges and mouse holes. The TDR method (Topp et al., 1980) adapted in this study enables continuous measurement of soil moisture content at limited number of spots, but has limitation in the applicability for wider area. As this study showed, the measurement of delay of heading provides rice water stress information in wider areas. It is specially effective in Northeast Thailand, where dominating rice cultivars of KDML 105 and RD 6 have strong photoperiod sensitivity and reach heading stage almost at a fix day under no water stress conditions, independently of transplanting or seeding dates (Ohnishi et al., 1999a; Miyagawa, 1995; also see Chapter 5).

As amount and pattern of precipitation is quite different among years and places in Northeast Thailand (KKU-FORD, 1982), field water availability fluctuates temporally and spatially. Normal precipitation in the investigated area exceeds those in the investigated years. Also, statistical analysis of precipitation indicated that dry spell of more than 2 weeks rarely happened from August to September period and most rainy seasons ended in mid-October as in the investigated years (Vorasoot et al., 1985; also cf.

Polthanee, 1996). It suggests that fields where heading of rice didn't delay in both years are classified not to drought-prone but to favorable or submergence-prone. The fields belonging to this classification occupy more than half of the area. Continuous investigation of heading time is needed for classifying field types more accurately, but the result may easily be expanded for wider area for assessing field water availability which significantly changes with the toposequence. The field classification based on rice response to the water availability is useful to develop strategies not only for breeding but also crop and field managements, which is definitely important for sustainable development of rainfed rice cultures.

Summary

Drought is recognized as the primal constraints for rainfed rice production. This study investigated spatial distributions of heading date of rainfed rice and field water conditions for two years in mini-watersheds called *Nong* in Thai in Northeast· Thailand, in order to clarify the toposequential variation in the degree of rice water stress. Despite only a few meter difference in the relative field elevation in the mini-watersheds, water availability in terms of standing water and soil moisture plainly decreased with ascending the elevation. Rice cultivars, KDML 105 and RD 6, the two dominant genotypes in Northeast Thailand, reached heading stage almost at a fix day under no water stress conditions, independently of transplanting or seeding dates under custom managements. As the decrease in the water availability with ascending the field elevation, rice heading markedly delayed. The delay of heading seemed to respond to the cumulative water stress before the heading of rice. The observed toposequential distribution of heading date indicated that practically no water stress developed at least half fields of the mini-watersheds. These results suggests that delay of

heading is a good index for rice water stress in Northeast Thailand and can be applicable to field classification with respect to drought risk.

Keywords: heading date; number of flooded days; soil moisture content; standing water; water stress;

Biomass Production of Rainfed Rice as Affected by Toposequential Distributions of Soil Fertility and Water Availability

Rainfed rice yield in Northeast Thailand is quite low and unstable, due to drought and low soil fertility (Miyagawa and Kuroda, 1988; Fukai et al., 1998). Those two constraints are extremely variable depending on toposequential position of fields in mini-watersheds, which is a component unit of topography there and called *Nong* in Thai. Chapter 1 showed that soil fertility decreased with ascending field elevation in mini-watersheds, and that soil organic carbon (SOC) content was a good index of soil fertility. Chapter 2 clarified that water availability also decreased with ascending field elevation, and heading date of dominant rice cultivars KDML105 and RD6 varied with the field elevation reflecting the water availability.

Ohnishi et al. (1999b) reported that without severe water stress, rice growth in Northeast Thailand was limited by plant nitrogen (N) uptake and that maximum yield of 4 t ha^{-1} was obtained for KDML 105 at N uptake of 90 kg ha^{-1}. Fertilizer experiments conducted at rainfed fields in Northeast Thailand also indicated that N is the most effective chemical fertilizer (Nakamura and Matoh, 1996; Wade et al., 1999a), and its recovery rate was 25 – 35 % (Khunthasuvon et al., 1998; Ohnishi et al., 1999b). It was shown that organic matter application improve soil fertility and rainfed rice yield (Wonprasaid et al., 1996; Whitbread et al., 1999). Results of chapter 1 and 2 suggest that optimum soil fertility managements based of those previous studies strongly depend on toposequential field position in a mini-watershed in Northeast Thailand. For improving rainfed rice yields, toposequential distribution of production potential needs to be clarified. This chapter aims to evaluate toposequential distribution of biomass productivity of rainfed rice as a function of soil fertility and water availability in a mini-watershed in Northeast Thailand.

Materials and method

Field investigation was done for a closed mini-watershed (*Nong*) of Hua Don Village located at about 25 km northwest from the Center of Ubon Ratchathani City; the area extends along Se Bai River, a branch of Moon River. At the mini-watershed, we selected 7 fields that belong to one farmer in 1997 and 12 fields belong to three farmers in 1998. Toposequential positions of investigated fields were presented with the field elevation relative to the lowest paddy field in the mini-watershed. Soils at the site are classified to Pimai and Ubon series according to the soil map published by Department of Land Development, Thailand (Changprai et al., 1971). Investigations were made of growth of rice, soil moisture (SM) and soil organic carbon (SOC) content.

Rice plant was harvested for measurements at transplanting time (TP) and every 10 days from 24 September to maturity (MT) in 1997, and .at TP, panicle initiation (PI), heading (HD) and MT in 1998. On each harvesting occasion, 4 rice hills from each of four replication spots in each field were harvested. The harvested plants were subjected for determination of dry weight and N content of each organ, and leaf area index (LAI). N content was determined by near infrared spectroscopic analysis method (BRAN + LUEBBE, Infra Analyzer 500) equipped with IDAS software, calibrated with Kjeldahl method.

Soil moisture (SM) content was measured twice a week from the end of August to harvest in 1997 and mid September to harvest in 1998 by TDR method (Sony Techtronics 1502B) (Topp et al., 1980). A 20 cm-length TDR tri-probe was vertically inserted into soil at 2 points at each field. Plow layer soils were sampled after first plowing in June 1998. Sampled soils were air-dried, cracked, passed through 1 mm-mesh sieves to remove plant residues. Soil organic carbon (SOC) content was measured for each soil by Walkly and Black method (Walkly and Black, 1934).

Rice cultivar RD6 was grown at all the harvested fields both years. A compound fertilizer with N – P_2O_5 – K_2O contents of 16 – 20 – 0 % was used in 1997, and 16 – 16 – 8 was used for all farmers in 1998. Fertilizer application rates for the respective fields were obtained from interviews to farmers, which varied 0 ~ 3.5 g N m^{-2}. Irrigation by pumping was conducted only once at transplanting time, if necessary.

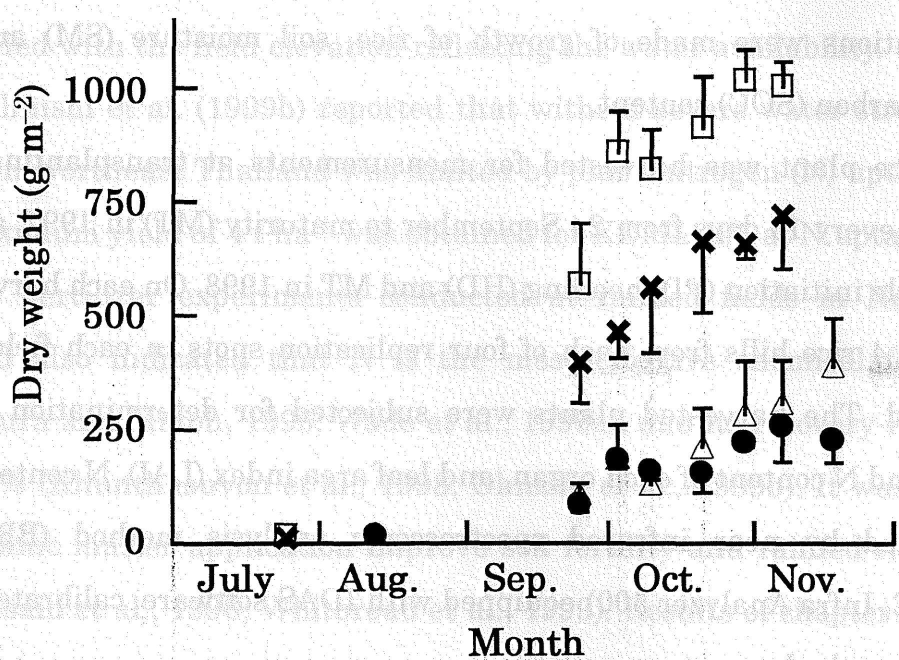


Fig. 3. 1. Time courses of above ground dry weight of rice grown at farmer's fields at different relative elevations in Northeast Thailand, 1997. Relative field elevations of □, ✖, △ and ● were 0.23, 0.67, 1.24 and 1.92 m, respectively. Error bars show s. d.

Results

Fig. 3.1 gives biomass growth curves of rice at different relative field elevations in the mini-watershed. Rice growth rate was larger at lower field. Both above ground and panicle dry weight at maturity had close negative correlations with the relative field elevation at the mini-watershed (Fig. 3.2). While rice plant grown at the lowermost field produced 1170 g m^{-2} biomass and 430 g m^{-2} panicle dry weight, that at the uppermost did only 160 g m^{-2} biomass and 11 g m^{-2} panicle. The difference in the biomass productivity was associated with that in rice nitrogen (N) uptake (Fig. 3.3). Above ground and panicle dry weight were proportional to their N content at all phenological stages in spite of difference in years and field elevations. Leaf area index (LAI) was also proportional to plant N uptake. The maximum LAI among the

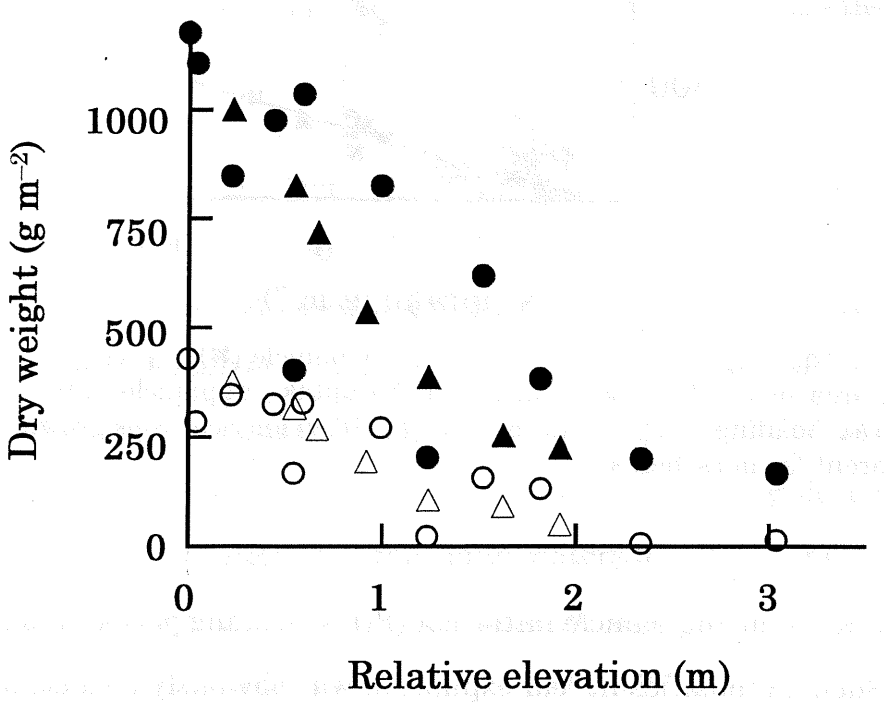


Fig. 3. 2. Above ground (close) and panicle (open) dry weight as a function of relative field elevation of farmers' fields in the mini-watershed in Northeast Thailand in 1997 (triangle) and 1998 (circle).

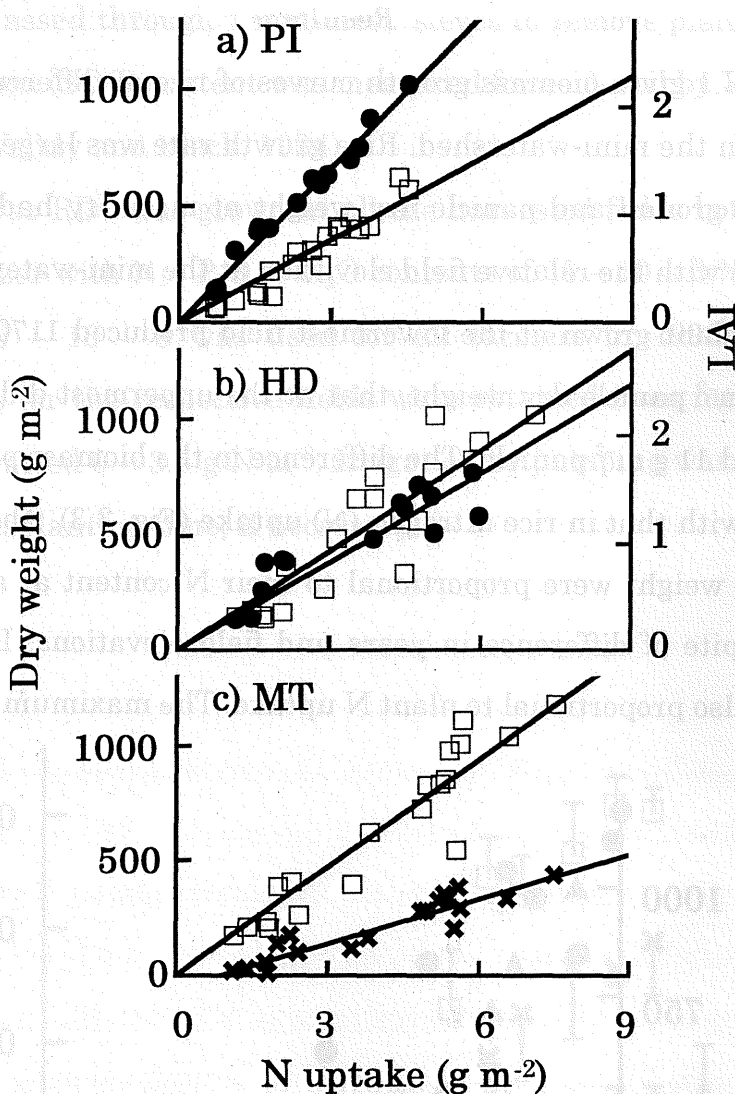


Fig. 3. 3. The response in above ground (□), panicle (✖) dry weight and leaf area index (LAI, ●) to nitrogen (N) uptake at panicle initiation (PI, a), heading (HD, b) and maturity (MT, c) for rice crops grown at different farmers' fields.

investigated fields during panicle initiation (PI) to heading period was as low as about 2. Such an insufficient leaf expansion was obviously a cause for the low productivity in rice biomass and yield at farmers' fields.

Time changes in N uptake of rice showed similar feature as that of biomass (Fig. 3.4). Although values were slightly scattered, N uptake increased almost linearly until heading (HD) with larger values at lower

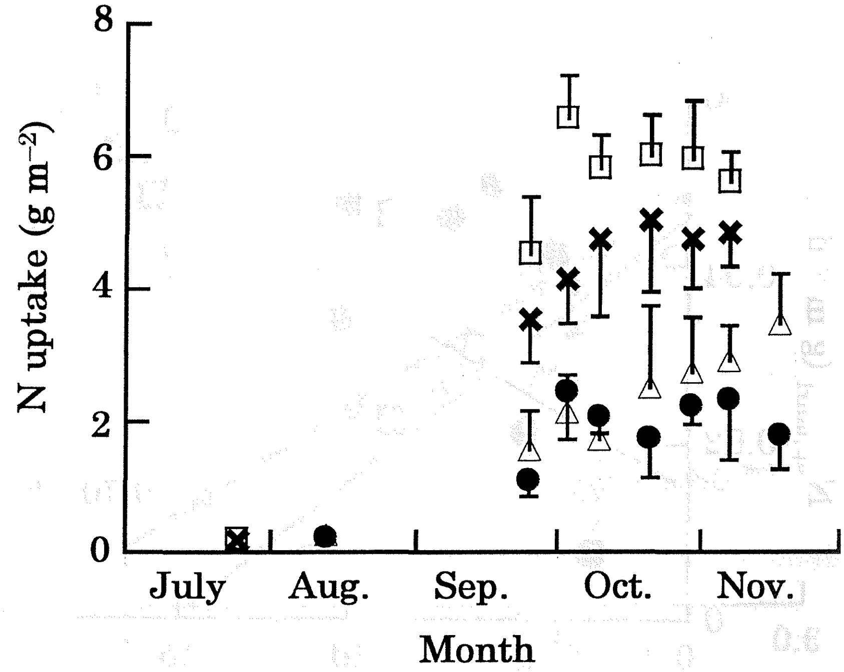


Fig. 3. 4. Time courses of nitrogen (N) uptake in rice grown at farmer's fields at different relative elevations in 1997. Symbols are the same in Fig. 3. 1.

field. The fertilizer N recovery rates at rainfed lowland in the vicinity areas of our research site were reported to be 25-35% (Khunthasuvon et al., 1998; Ohnishi et al., 1999b). By assuming the N recovery rate of 30% and using the data of farmers' fertilizer N application rates on the fields of investigation, rice uptake rate of mineralized soil N ($N_{up,mnrl}$) for the period from transplanting (TP) to HD was estimated. $N_{up,mnrl}$ generally decreased with ascending field elevation in the mini-watershed, and the correlation coefficient between $N_{up,mnrl}$ and relative field elevation was 0.69 ($P < 0.01$).

It is considered that the toposequential variation in $N_{up,mnrl}$ is affected by those in soil fertility and water availability, both of which were scarcer at upper fields and richer at lower. The previous studies (Chapter 1 and 2) showed that soil organic carbon (SOC) content and soil moisture (SM) at rice reproductive period are good indexes of soil fertility and water

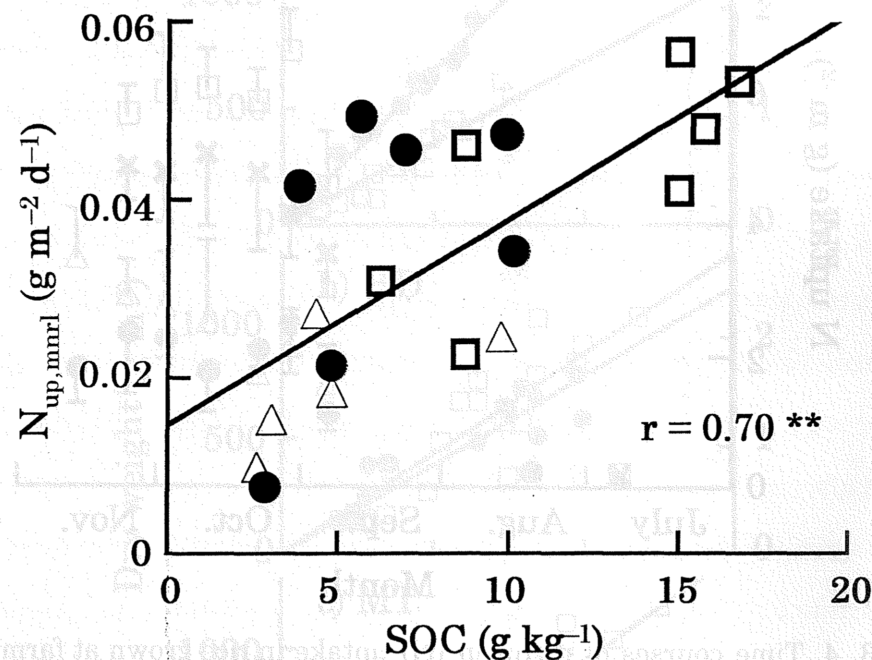


Fig. 3. 5. Rice uptake rate of mineralized soil nitrogen ($N_{up,mnrl}$) as a function of soil organic carbon (SOC) and soil moisture content during the reproductive period at farmers' fields in 1997 and 1998. Soil moisture contents averaged for the period from panicle initiation to heading were 0 ~ 0.3 (△), 0.3 ~ 0.4 (●) and 0.4 m^3 m^{-3} ~ (□).

availability, respectively. To understand which indexes gives significant effect on $N_{up,mnrl}$, correlation coefficients between $N_{up,mnrl}$ and these indexes were calculated. Both SOC and SM were closely related to $N_{up,mnrl}$, thereby SOC having slightly larger correlation coefficient than SM. In Fig. 3.5 where the rates of $N_{up,mnrl}$ were presented as a function of SOC and SM, SOC and $N_{up,mnrl}$ relationship are fairly independent of SM. This suggests that $N_{up,mnrl}$ was restricted by SOC than SM.

While biomass production is suggested to be more restricted by soil fertility, panicle dry weight was affected by water availability. harvest index (HI, panicle dry weight divided by above ground biomass weight) had a close correlation with soil moisture content during the period from PI to HD (*r* =

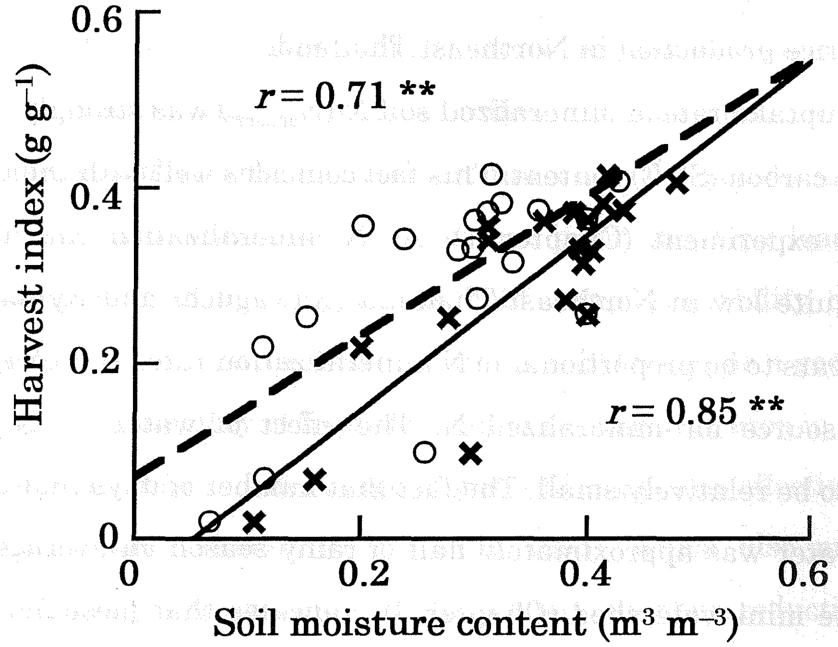


Fig. 3. 6. Relation between harvest index of rainfed rice and soil moisture content for farmers' fields at different relative elevations in 1997 and 1998. Soil moisture content was averaged for the period from panicle initiation to heading (✖, solid line) and from heading to maturity (O, broken line).

0.85, P< 0.01), while the correlation between HI and SOC was 0.43 (Fig. 3.6). Fig. 3.6 also indicates that soil moisture from PI to HD affected panicle dry weight more severely than that during grain filling period.

Discussion

This study aims to clarify toposequential variability in rice biomass production based on toposequential distribution of environmental resources. The results shown above indicate that biomass production in the rainfed rice was primarily restricted by plant nitrogen (N) uptake in all the fields investigated. The N sources for rice uptake are soil mineralized and fertilized N. Since farmers at the investigated fields applied small amount of

N fertilizer (0 ~ 3.5 g N m^{-2}), N derived from fertilizer only occupied less than 25 % of total N uptake. It indicates that N mineralization is quite important for rainfed rice production in Northeast Thailand.

Rice uptake rate of mineralized soil N ($N_{up,mnrl}$) was strongly related to soil organic carbon (SOC) content. This fact coincides well with the results on potted rice experiment (Chapter 1). As N mineralization rate in soil is generally quite low in Northeast Thailand (Kawaguchi and Kyuma, 1969), $N_{up,mnrl}$ appears to be proportional to N mineralization rate. Therefore, SOC is important source for mineralized N. The effect of water on $N_{up,mnrl}$ was suggested to be relatively small. The fact that number of days that fields had standing water was approximately half of rainy season on average over all fields in the mini-watershed (Chapter 3), indicates that most field did not have abundant water. Even under limited water availability condition, present study indicates that soil fertility limits rice growth more strongly than the water availability.

Water stress causes reduction of leaf area and dry matter production (Fuaki and Cooper, 1995; Wopereis et al., 1996). It was also reported that leaf area and biomass often increase more than normal after removal of water stress (Bañoc et al., 2000; Wade et al., 2000). Such a compensating effect of water stress was only slight but also observed in this study. This, together with uniform temporal precipitation distribution observed in the research site (see Fig. 2.2), may suggest a relatively smaller water stress effect on rice biomass production. The relatively smaller effect of water stress can be seen in the relationship between nitrogen (N) uptake and rice biomass production shown in Fig. 3.3. Fig. 3.3 indicated that above ground dry weight was proportional to N uptake passing the origin, while panicle dry weight, which was more affected by drought, had minus interception against N uptake.

It was reported that late season drought gave more severe effect on rice yield in general in rainfed rice (Fukai et al., 1998; Jongdee et al., 1997). However, results of this study showed that soil moisture content from panicle initiation (PI) to heading (HD) more severely affected rice yield than that during grain filling. This seemed to reflect the fact that soil moisture gradually decreased after the heading around which dry season started, and that under such condition low soil moisture before heading lead to lower moisture after it (Fig. 2.4). Thus, the field water availability during the reproductive period of cultivars KDML 105 and RD 6 can be a good index of seasonal water availability of fields in rainfed rice farming area in Northeast Thailand. Water stress at later stage of grain filling is less effective to grain filling (Kobata and Takami, 1979; Tsuda 1993), which also may partly explain the larger pre-heading water stress effect. Further, reduction of sink size, which was caused by water stress during the reproductive period (Wada et al., 1945; Tsuda and Takami, 1991), led to the reduction of the harvest index of rice.

Regardless magnitude of water stress, biomass production was strongly limited by mineralized soil N. Previous studies showed that incorporation of organic matter was one of the methods for improving soil fertility (Herrera et al., 1997; Konboon et al., 1998). Cultivar difference in N uptake rate was shown to be small under low soil fertility conditions (Tirol-Padre et al., 1996; Ohnishi et al., 1999b). Under extremely low soil fertility conditions in Northeast Thailand, longer growth duration endured by earlier transplanting help rice uptake more N. Longer growth duration also increases rice solar radiation interception with small leaf area.

Summary

Water availability and soil fertility change with field toposequential position in mini-watersheds in Northeast Thailand. This study aims to clarify how biomass production of rainfed rice in a mini-watershed is affected by the distribution of these environmental resources based on field measurements of soil moisture and growth and nitrogen (N) uptake of rice. Dry matter production and yield of rice had close negative correlations with the relative field elevation, and they were more limited by plant N uptake than the soil moisture conditions. The N uptake increased almost linearly until heading. Average uptake rate of mineralized soil N ($N_{up,mnrl}$) for pre-heading period, estimated by assuming some recover rate as fertilized N, generally decreased with ascending field elevation. The $N_{up,mnrl}$ was strongly related to soil organic carbon content (SOC). These results suggest that SOC is a good index of soil fertility in rainfed rice area in Northeast Thailand. Although the effect of soil moisture on rice biomass production was relatively small, the harvest index (panicle dry weight divided by above ground biomass weight) was strongly affected with soil moisture content. It was indicated that soil moisture from panicle initiation to heading gave significant effect on rainfed rice through its effect on the harvest index.

Keywords: biomass production; harvest index; nitrogen uptake; soil fertility; water availability;

Rainfed Rice Yield as Affected by Toposequential Distribution of Soil Fertility and Water Availability, and Farmers' Crop Managements

In Northeast Thailand, 91 % of rice fields are classified to rainfed, and rice yield there is as low as 1.7 t ha^{-1}. It is pointed out that rainfed rice yield is not only very low but also quite variable in Northeast Thailand due mainly to low soil fertility and drought (Fukui, 1993; Wade et al., 1999b; Fukai et al., 1998). Previous studies clarified that soil fertility and water availability changed with toposequential position in mini-watersheds, which are distinct topographical components of rainfed rice farming areas in Northeast Thailand and called *Nong* in Thai (Chapter 1 and 2). These environmental resources were rich at bottom of mini-watersheds, while they were scarce at uppermost. Biomass and panicle production of rice was strongly affected by the toposequential distribution of environmental resources (Chapter 3).

Besides the toposequential distributions of environmental resources, farmers' crop managements also may give large effects on rainfed rice yield. In recent years, chemical fertilizers are commonly used by farmers in Northeast Thailand, although the application rates are very low (Miyagawa et al., 1999; Pandy, 1998). For KDML 105 and RD 6, the most widely cultivated rice cultivars in Northeast Thailand, which have a definite heading time irrespective of transplanting time, transplanting time is quite important for enduring sufficient growth duration and hence for yield (Chapter 3; also described in detail in Chapter 5). Adaptability of farmers' management to field standing water conditions is also an important factor for consideration (Fukui, 1993; Miyagawa, 1995).

Under such diverse field environmental conditions in rainfed rice culture in Northeast Thailand, rice production technologies (i.e. cultivars and crop and resource managements) for improving the productivity should differ depending on toposequential field conditions. Under this idea, this chapter aims to clarify the field-to-field difference in rainfed rice yield in relation to toposequential distributions of environmental resources and farmers' crop managements in mini-watersheds in Northeast Thailand based on field investigations.

Materials and method

Field investigation was done for a rainfed rice culture area located at about 25 km northwest from the Center of Ubon Ratchathani City; the area extends along Se Bai River, a branch of Moon River. One-farmer's fields at the mini-watershed (*Nong*) of Hua Don Village was selected for investigation in 1997 and investigation fields were expanded to 4 mini-watersheds in 1998 as shown in Fig. 1.1 in Chapter 1. The investigation site at Hua Don Village in 1998 was 9.3 ha in the area (see Fig. 2.1), in which the elevation of the uppermost field relative to the lowermost was 3.4 m. The site included the farmer's fields investigated in 1997, which is noted as No. II farmer in Fig. 2.1. The investigation sites at other three locations covered fields along traverse lines along the slopes of mini-watersheds. The traverse lines at Wang O, Kha Khom and Mak Phrik Village were about 200, 500 and 150 m in the length and 6.0, 1.5 and 2.6 m in the difference in the relative field elevation, respectively. Field elevation was represented as relative to the lowest paddy field at each research site. In Hua Don site, fields were classified into three positions lower (0 ~ 0.5 m), middle (0.5 ~ 1.5 m) and upper (1.5 m ~). The numbers of farmers farming the rice fields at the sites of Hua Don, Wang O, Kha Khom and Mak Phrik were 10, 1, 6 and 1, respectively. Table 4.1 shows statistical summary of differences among research sites in soil organic carbon (SOC) and clay content and number of flooded days in wet season in 1998.

Rice biomass and rough grain yields were measured for 21 spots in 7 fields in 1997, 275 spots in 194 fields at Hua Don, 15 spots in 5 fields at Wang O, 21 spots in 7 fields at Kha Khom and 12 spots in 4 fields at Mak Phrik in 1998. Each reaping area was about 1 m^2 in 1997 and 0.5 m^2 in 1998. At all the fields of investigation either cultivar KDML105 or RD6 was grown. At Hua Don site in 1998, above ground weight of weeds was also investigated for 228 spots in 162 fields. Amounts, dates and places of chemical fertilizer applications to the investigation fields were recorded by author's observations and interviews to farmers. Also number and kind of livestock that each farmer has was investigated by the interviews. Dates of Seeding or transplanting, heading of rice and harvesting were monitored and recorded for all the fields.

Table 4. 1. Difference in soil organic carbon (SOC) and clay content and number of flooded days in wet season in 1998 among research sites (data from Chapter 1 and 2).

Site	SOC (g kg^{-1})	Clay (%)	Flooded days (d)
	ave. ± s.d.	ave. ± s.d.	ave. ± s.d.
Hua Don	7.86 ± 5.02	12.87 ± 13.82	48.85 ± 41.84
Lower	13.07 ± 4.87	25.71 ± 13.34	87.75 ± 32.83
Middle	6.71 ± 2.44	10.10 ± 11.96	65.88 ± 28.64
Upper	3.92 ± 2.17	3.06 ± 0.86	6.90 ± 15.15
Wang O	3.03 ± 1.03	6.20 ± 2.73	78.20 ± 23.38
Kha Khom	5.01 ± 1.84	13.42 ± 14.78	104.50 ± 42.01
Mak Phrik	4.28 ± 2.42	6.62 ± 2.52	28.00 ± 54.15

Table 4. 2. Rice acreage, management and livestock holds by farmers at the respective research sites.

Site Farmer[1]	Paddy field area (m^2)	Transplanting date	Harvesting date	N fertilizer (kg ha^{-1})[2]	FYM[3]	Live-Stock[4]
Hua Don research site in 1997.[5]						
II		15 July ~ 13 Aug.	9 ~ 18 Nov.	35.0	O	Ca 1
Hua Don research site in 1998.						
I	3566	25 June ~ 12 Aug.	6 ~ 10 Nov.	22.4	O	W 1
II	9870	17 July ~ 12 Aug.	6 ~ 18 Nov.	14.4	O	Ca 1
III	21803	25 June ~ 11 Aug.	6 ~ 18 Nov.	17.6	O	W 3
IV	618	6 July	9 Nov.	12.9	X	
V	5548	26 June ~ 12 Aug.	7 ~ 18 Nov.	40.2	O	W 2
VI	4117	7 July ~ 6 Aug.	10 Nov.	45.3	X	
VII	11201	9 July ~ 25 July	7 ~ 9 Nov.	14.3	X	
VIII	4503	13 July ~ 17 July	9 Nov.	65.0	O	W 4
IX	18942	4 July ~ 15 Aug.	6 ~ 18 Nov.	13.4	O	Ch 200
X	12767	14 July ~ 13 Aug.	6 ~ 18 Nov.	26.5	O	W 5
The other sites in 1998.[5]						
Kha Khom		25 June ~ 30 July		16.1	1 / 6 [7]	W 1
Wang O		1 July ~ 6 July		15.0	1 / 1 [7]	Ca 6
Mak Phrik		23 July ~ 15 Aug.		– [6]	0 / 1 [7]	

[1] No. I to X farmers in Hua Don research site are corresponded to those in Fig. 2.1.

[2] N fertilizer rate was estimated by dividing the farmer's total application by acreage.

[3] FYM: Farm yard manure, O: applied and X: not applied.

[4] Kinds and number of livestocks as main source for FYM. W: water buffalo, Ca: caw and Ch: chicken. The numerals attached to livestocks indicate the number of animal.

[5] Values are average of fields where research was conducted.

[6] Quite small amount of fertilizer.

[7] The numerator is the number of farmers who applied FYM and the denominator is the number of farmers at the research site.

Results

1. Farmers' crop managements

In general, farmers applied farmyard manure (FYM) at the end of dry season and its amount was related to their ownerships of livestock as shown in Table 4.2. In all the investigation sites, farmers started to plow paddy fields and simultaneously to make nursery beds in June after rainy season started.Nursery beds were made at paddy fields located at middle parts of slope of each mini-watershed. Transplanting was done from the end of June to the middle of August and from lower to upper fields in each mini-

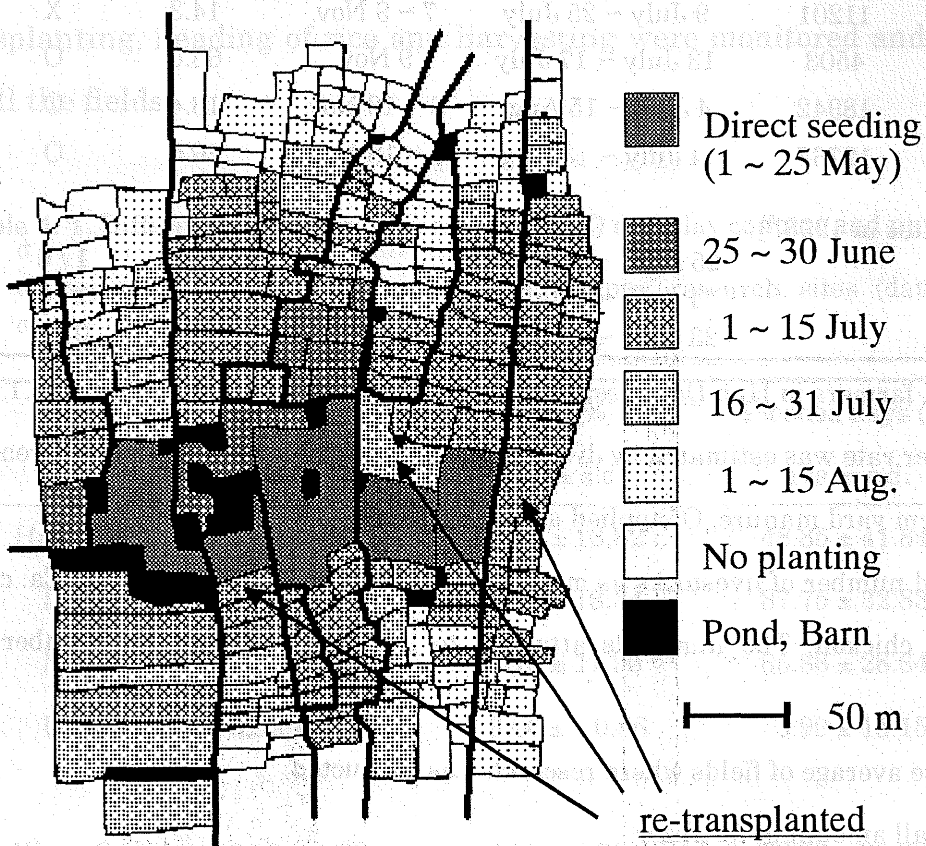


Fig. 4. 1. Map showing the date of direct seeding or transplanting of each field at Hua Don research site in 1998.

watershed, with one- to two-month-old seedlings (Fig. 4.1). Some bottom fields only at Hua Don research site were direct seeded. In some of direct seeded fields where farmers failed in seedling establishment, seedlings were re-transplanted. The fields used for nursery beds were either transplanted afterwards or unused. Most farmers in the research sites applied chemical fertilizer once or twice during rice growth: one after the completion of transplanting on all the fields, and if preferred, another on mid September (around 30 days before heading). Since combined chemical fertilizer, 16-16-8 % ($N-P_2O_5-K_2O$) type, was most popular, the amount of fertilizer was described by its nitrogen amount here after. Fields around the top of the mini-watersheds weren't applied with fertilizer because of high risk of water shortage, while fields around the bottom were also not applied because of high risk of flow out with flood. Hand weeding was conducted only once at transplanting time. Pumping water was also irrigated only at transplanting time if needed. Heading time of KDML105 and RD6 both were usually in the middle of October, the end of rainy season, under their practices, provided no hard damages by water shortage (Chapter 2). Rice was harvested successively from the bottom to upper fields at each site during November.

To sum up, transplanting and harvesting time were almost determined by water availability. Thus, those practices were different among toposequential field positions, but not so different among farmers (Table 4.2 and 4.3). Although fertilizer application was also affected by the condition of standing water, it also depended on farmers' strategy for reducing economical risk and ensuring food security, resulting in large difference in the amount among farmers. Since not only soil fertility but also water availability was quite low in Mak Phrik site, the farmer rarely took care his paddy fields.

Table 4. 3. Differences in farmer cultural practices for lower, middle and upper rice fields across the toposequence of the Hua Don study area, Northeast Thailand, 1998.

Farming activity	Toposequential position (relative elevation in m) [1]		
	Lower (0–0.5)	Middle (0.5–1.5)	Upper (>1.5)
Transplanting (DOY)[b]	189th ± 11 a	198th ± 11 b	210th ± 13 c
Harvesting (DOY)[b]	313th ± 2 a	315th ± 2 b	316th ± 4 c
Fertilizer (N at kg ha^{-1})	26.8 ± 23.7 a	37.6 ± 18.4 b	13.7 ± 25.0 c

[1] Values within a column followed by the same letter are not significantly different at the 5% level.

[2] DOY = day of the year, for example, 189th ± 11 = 8th July ± 11 days.

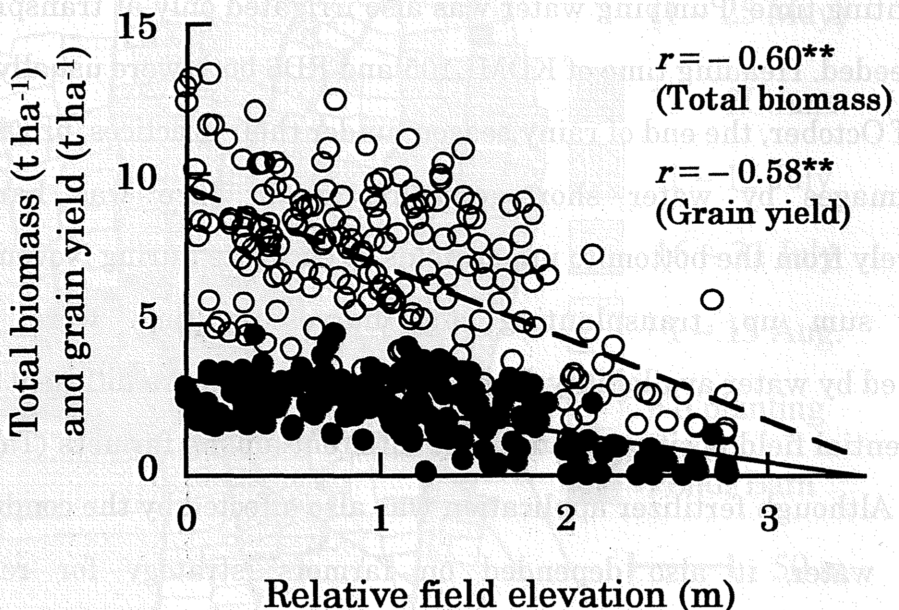


Fig. 4. 2. Variation with field elevation in total biomass (O) and grain yield (●) in the Hua Don study area, Northeast Thailand, 1998.

2. Rice yield

Although quite large variation in the biomass and grain yields were recognized among the fields at a same relative elevation, both the growth attributes declined with ascending the field elevation at Hua Don site (Fig. 4.2). The biomass and grain yields were correlated to the relative field elevation at $r = -0.60$ ($P < 0.01$) and $r = -0.58$ ($P < 0.01$), respectively. Similar relations were also observed at the other sites (data not shown). The production tendency against field elevation was mostly derived from toposequential distribution of soil fertility and water availability, both of which were rich at lower paddies and insufficient at upper (Chapter 1, 2). This is confirmed by the statistical analysis data of rice growth attributes at different toposequential positions at Hua Don site (Table 4.4). Fields at the lower position produced more dry matter than the middle in spite of less amount of fertilizer application, which indicates that the rich environmental resources at the lower position fields play important role for rice growth.

Table 4. 4. Differences in rice growth and yield among the lower, middle and upper fields across the toposequence of the Hua Don study area, Northeast Thailand, 1998.

Crop parameter	Toposequential position [1]		
	Lower	Middle	Upper
Total dry matter (t ha^{-1})	8.42 ± 2.37 a	7.22 ± 2.28 b	4.12 ± 2.43 c
Grain yield (t ha^{-1})	2.63 ± 0.62 a	2.50 ± 0.86 a	1.13 ± 0.97 b
Harvest index	0.325 ± 0.069 a	0.345 ± 0.055 a	0.225 ± 0.121 b

[1] Values within a column followed by the same letter are not significantly different at the 5% level.

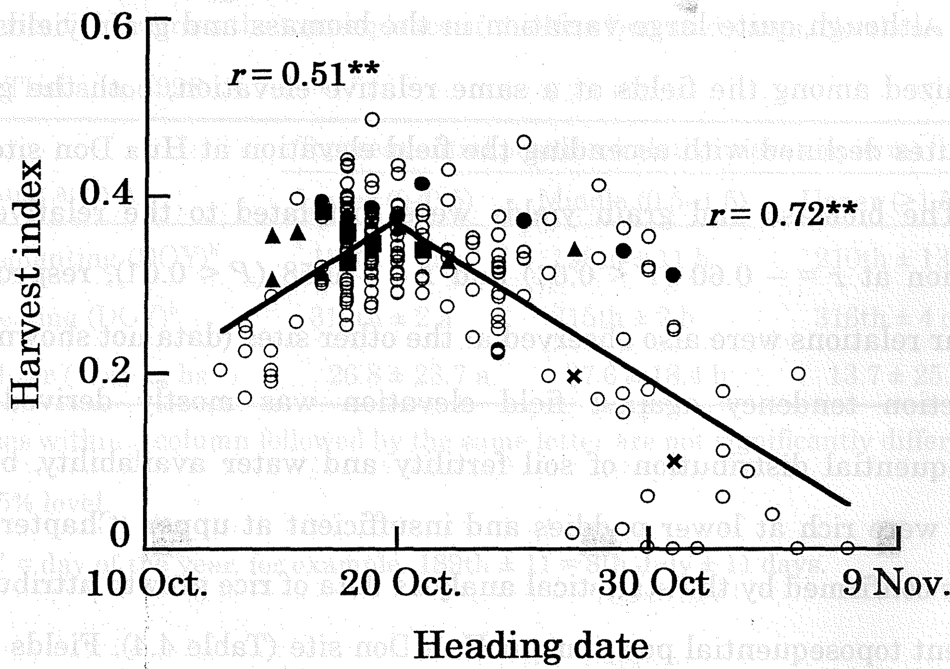


Fig. 4. 3. Relation between heading date and harvest index in rice grown at farmers' field. ● Hua Don in 1997, and ○ Hua Don, ■ Wang O, ▲ Kha Khom and ✖ Mak Phrik in 1998. Liner regressions were separately calculated for the heading dates from 13 to 20 October and from 20 October to 7 November.

However, the grain yield was not significantly different between the lower and the middle fields, reflecting the slightly lower harvest index (HI) at the lower fields. This seemed to be due to lodging at the lower field. As rice heading day was shown to be a good index of field water availability (Chapter 2 and 3), the relation between the heading day and HI was analyzed and shown in Fig. 4.3. The earlier heading indicates less water stress at lower fields, where the lower harvest index was likely to be caused by the lodging. With the exception of this, rice headed later had lower HI. The relation of HI with the heading date wasn't different among mini-watersheds investigated. Previous studies showed that not only low soil moisture content during grain filling but also that before heading caused the

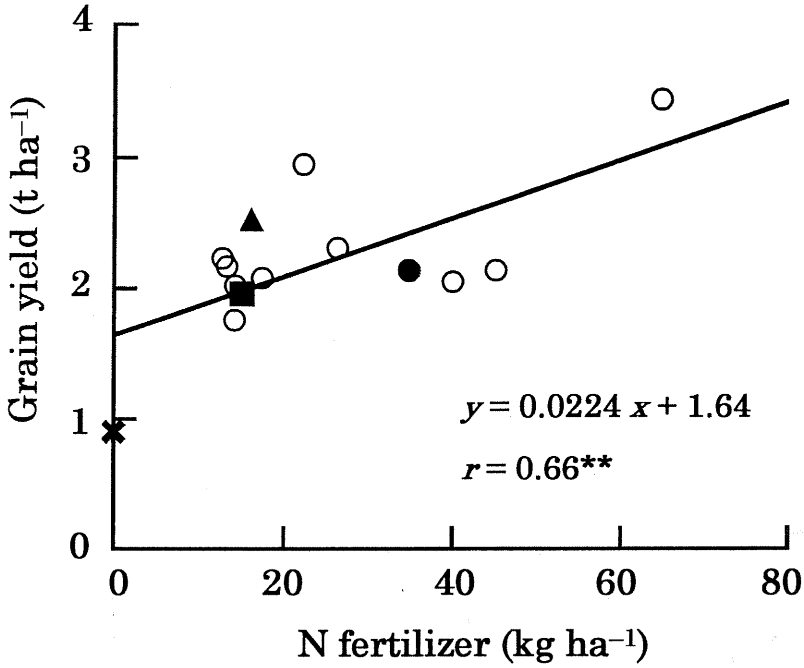


Fig. 4. 4. Grain yield as a function of amount of chemical nitrogen (N) fertilizer at micro-watersheds in Northeast Thailand. Symbols are the same as in Fig. 4. 3.

decline of HI (Chapter 3).

Farmers who applied more amount of fertilizer tended to have better grain yield (Fig. 4.4). The relationship between fertilizer application rate and the yield ($r = 0.66$, $P < 0.01$) was considerably firm in spite of the difference in the soil fertility and water availability. Agronomic efficiency of nitrogen (yield increase per unit applied nitrogen) was 0.0224 t kg^{-1}, which was similar to those experimentally obtained in Northeast Thailand (Khunthasuvon et al., 1998; Ohnishi et al., 1999).

Relation between rice and weeds biomass productions for different fields was shown in Fig. 4.5. Weeds biomass enormously differed among fields, but only slightly among farmers. On average over all fields investigated the weeds biomass production was 18.3 % of that of rice. In some fields, weeds biomass exceeded rice biomass production. Except for such fields, toposequential distribution of rice biomass production did not have any clear relation to weeds production.

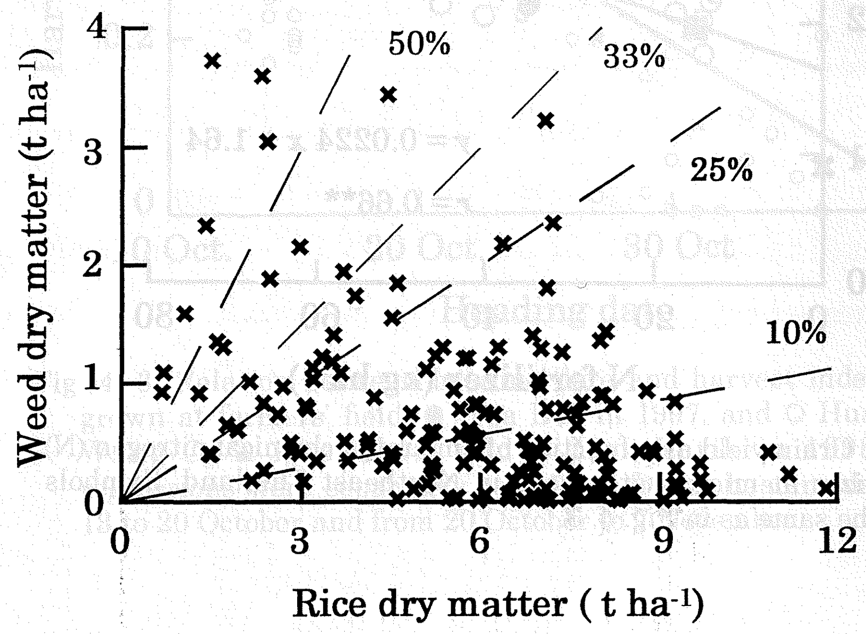


Fig. 4. 5. Weeds dry matter production against rice dry matter at rice harvest for different fields at Hua Don research site in 1998. Percentage means weed proportion to total (rice + weed) dry matter.

Discussion

The field investigation in this study quantified toposequential distribution of rice yield at mini-watersheds in Northeast Thailand. The existence of the toposequential variability within rather small areas was suggested by Wade et al (1999b), and well known experientially to farmers. Farmers' management of transplanting and fertilization was well adapted to the distribution environmental resources. The field ownership, in which each farmer has his field along the slop of mini-watersheds as shown in Fig. 2.1, can be regarded as an adaptation to the toposequential gradient of environmental resources (Craig and Pisone, 1988; Fukui, 1993).

As lower paddy fields have risk of submergence, early transplanting or direct seeding is practiced. Later transplanting at the upper fields is associated with lack of standing water, which is unavoidably accompanied with a reduced growth duration. Soil moisture content was maintained almost constant in rainy season (Fig. 2.4), the late transplanting did not help avoid from water stress. For reducing water stress effect at the upper fields, using such early maturity varieties as farmers used to do (Fukui, 1993; Miyagawa, 1995) would be effective. Phenological development characteristics of KDML105 and RD6 were well adapted to ordinary moisture conditions in Northeast Thailand, but their delay of heading at droughty fields lead to more severe water shortage in grain filling period in dry season. The water stress associated with the delay of heading brings reduced harvest index (HI) as shown in Fig. 4.3. Jerakongman et al. (1995) also reported in their varietal trials that heading after disappearance of standing water brought yield reduction of rainfed rice.

Chemical fertilizer significantly increased rice grain yield on farmer basis. Field experiments of KDML 105 showed that a maximum grain yield of 4 t ha^{-1} was obtained at biomass yield of 10 t ha^{-1} and that biomass yield above this brought yield reduction by lodging and reduction of HI (Ohnishi et al., 1999b; Romyen, 1998). The results of this study showed that the yield at the lower fields was almost the maximum. Less amount of fertilizer application at the lower fields than that at the middle indicates that farmers know this empirically. This also suggests that rice yield increase can be attained with fertilizer application at middle and upper fields. Although such an application accompanies a risk of drought, it is surely worth to apply more amount of fertilizer. Economical analysis also indicated that risk management must be considered in rainfed conditions but the optimum amount of fertilizer was much more than the present level (Pingali et al., 1998).

Effect of farmyard manure (FYM) application wasn't significantly distinguishable as that of the chemical fertilizer in this field research. The reason for this was thought that its application level was quite low. For a significant effect, the amount of FYM needed was at least 3 t ha^{-1} (Songmuang et al., 1989), or about 6 t ha^{-1} if possible (according to farmers; Khunthasuvon et al., 1998). It is estimated that one water buffalo can produce about 0.5 t FYM $year^{-1}$ (Nakamura and Matoh, 1996). Numbers of livestock is short for producing adequate FYM amount except for No. VIII farmer. Since soil fertility was strongly related to soil organic carbon (Chapter 1), incorporation of FYM or other organic matter is important for sustainable production, even if its amount was small and its short-term effect was non-significant.

Previous chapter (chapter 3) suggested that maintenance of ridge so as to reduce water seepage had possibility to improve water availability and then productivity of rainfed rice. Weed management also had the possibility especially in those fields where weed biomass exceeded rice biomass. Herbicide weed control now started will be more popular in the future. For adaptation of these managements to farmers' fields to improve rainfed rice productivity there, toposequential distribution in rice productivity must also be taken into accounts.

Summary

Steep gradients exist across the toposequence in soil fertility and water availability in mini-watersheds which are geographically distinct components of rainfed rice farming areas in Northeast Thailand. Objectives were to clarify on the basis of field investigation, how the distributions of environmental resources and farmers crop managements affects rainfed rice yield in mini-watersheds, and to identify crop management technology for improving yield. The field investigation revealed that farmers' managements were fairly well adapted to the toposequential distribution of soil fertility and water availability. Transplanting was conducted from lower to upper fields, and more amount of chemical fertilizer was applied at middle fields. The transplanting day was not so difference among farmers, while the amount of fertilizer application was quite difference among farmers, ranging from 0 to 65 kg N ha^{-1}. The biomass yields of rice were reflected with these farmers' managements and the distribution of environmental resources, both of which were closely correlated to the relative field elevation. The grain yield also had a close correlation to the field elevation, with excepting that lower fields was not superior to middle field due to lodging. Farmers who applied more amount of fertilizer tended to have better grain yield. Although weed biomass exceeded rice biomass at some fields, its damages were considered not so large problem in general. Improvement in crop managements had possibility to increase rainfed rice productivity there; those include the adoption of early maturing cultivars at the upper fields, more fertilizer application to the middle to upper fields, adequate ridge managements to avoid water seepage, and weed control.

Keyword: farmers' management; fertilizer application; rice yield; soil fertility; transplanting date; water availability; weed;

Modeling the Toposequential Distribution of Rice Yield, Based on Soil Fertility and Farmers' Crop Managements

It was attempted to develop a general model that would evaluate rice production potential of rainfed lowland fields in relation to soil fertility and using water availability as a function of toposequence. A nitrogen-limited rice growth simulation model for simulating growth and yield was firstly developed, based on the toposequential distribution of soil fertility and farmer cultural practices. The objective was to examine the extent to which the observed toposequential yield variation can be explained by soil fertility and farmer cultural practices.

The model was synthesized by incorporating the processes related to soil N budget and plant N uptake into a previous model for simulating rice growth and yield based on plant N developed by Ohnishi et al. (1999a). This section briefly describes the synthesized model's structure and the results of applying it to simulate the toposequential distribution of rice yield in the mini-watershed of the Hua Don Village.

Overview of the model

The N-limited type model for simulating the growth and yield of rainfed lowland rice in Northeast Thailand is schematically represented in Fig. 5.1. The ontogenetic development of rice is quantified by a continuous variable of the developmental index (DVI), of which values are defined as 0.0 at emergence, 1.0 at panicle initiation, 2.0 at heading and 3.0 at maturity. Under this defining condition, the value of DVI at any moment of rice development is given by integrating the daily developmental rate (DVR) with respect to time. The DVR itself is a function of daily photoperiod and temperature. On the basis of rice growth experiments for various cropping

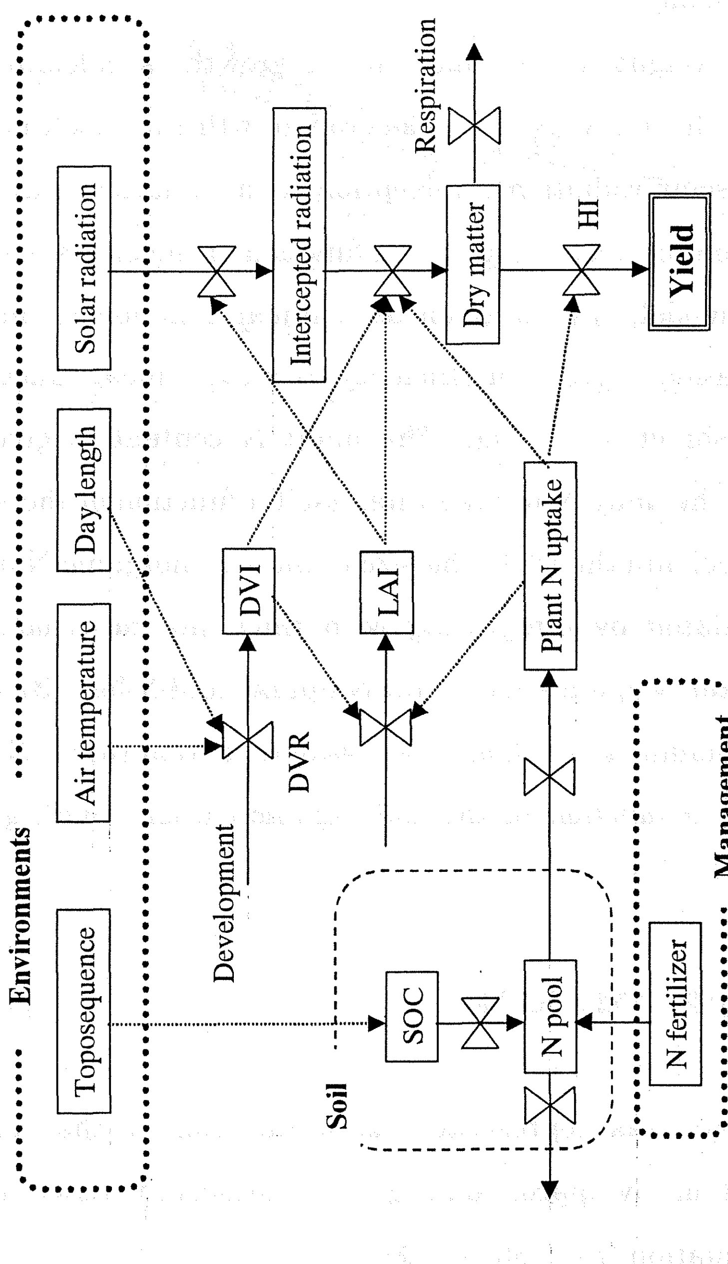


Fig. 5. 1. Flow chart of the model for simulating nitrogen-limited growth and yield of rice in relation to toposequential distribution of soil organic carbon (SOC) content and weather conditions. DVR: developmental rate, DVI: developmental index, LAI: leaf area index, N: nitrogen and HI: harvest index.

seasons at Ubon Rice Research Center (URRC) and at Kyoto University, the DVR response function to photoperiod and temperature was determined for cultivar KDML105, one of the two most widely grown rice genotypes in Northeast Thailand, using the SIMPLEX method (Horie and Nakagawa 1990; Ohnishi et al. 1999a).

The crop's dry weight at any moment of growth is calculated by integrating daily growth rate with time. The crop growth rate itself is given by multiplying daily solar radiation interception with radiation conversion efficiency. The radiation interception rate is a function of the crop's leaf area index (LAI). In this model, LAI is given as a linear function of plant N content, and the radiation conversion efficiency as a curvilinear function of the N content (Ohnishi et al. 1999a). The plant N content is given by integrating time with the daily N uptake rate, itself a function of the size of the soil inorganic-N pool and the DVI. The size of the soil inorganic-N pool at any moment is calculated by integrating with time, the rates of soil-N mineralization, fertilizer N application, plant N uptake and N loss. Based on the previous study (Homma et al. 1999), the N mineralization rate (ΔN_{min}, kg ha^{-1} d^{-1}) was given as a function of the soil organic carbon (SOC, g kg^{-1}) content as follows:

$$\Delta N_{min} = 0.657\ exp\{-3.52 / \mathrm{SOC}\} \qquad [1]$$

The SOC content was represented as a function of the relative elevation of fields (RE, m) by approximating the relationship shown in Fig. 5.2 by the following equation ($r = 0.86$, $P < 0.01$):

$$\mathrm{SOC} = 12.37\ exp\{-0.622\ \mathrm{RE}\} \qquad [2]$$

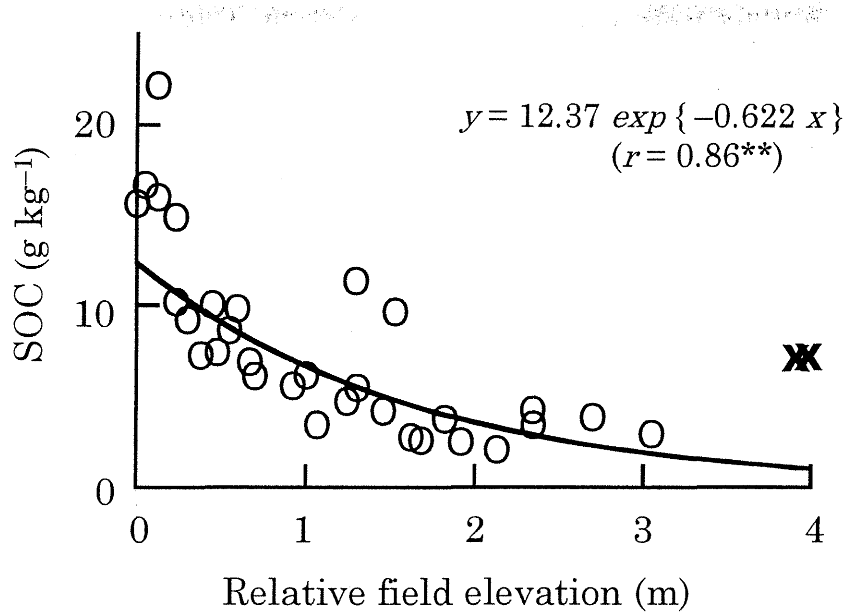


Fig. 5. 2. Soil organic carbon (SOC) contents as a function of the relative field elevation of farm fields in the Hua Don study area (O) and secondary woodland (X), Northeast Thailand.

The paddy rice yield is given by multiplying rice biomass with the harvest index (Horie et al., 1992).

The values for all the model's parameters were specified according to the results of (1) field experiments on 'KDML105' under different N management practices at the URRC (Ohnishi et al. 1999a), and (2) the field studies in the study area. The N-limited rice growth model with that parameter set explained fairly well the growth and yield of 'KDML105' grown under different N management practices and under no severe water stress conditions at the URRC (Ohnishi et al. 1999a).

A set of parameters for a high-yielding rice variety (HYV) was also prepared for the simulation by adopting the crop parameters of for 'IR64' as specified by Matthews et al. (1995). The HYV was a photoperiod-insensitive genotype, which had a higher harvest index and shorter time to maturity than did 'KDML105'. Daily solar radiation and temperature data obtained at the URRC in 1998 were used for the simulation. Daily photoperiods were calculated from latitude and were used for the simulation. Observed data for rice transplanting dates and farmer N applications were used to simulate rice growth and yield of 247 fields in the study area.

Simulation results

Fig. 5.3 gives, for the rice cultivar KDML105, the DVR response curve to the daily photoperiod under different temperatures. The high photoperiod sensitivity of this cultivar is well illustrated in Fig. 5.3 by the sudden decline of its DVR at its critical photoperiod (12.8 h).

The developmental process towards heading for 'KDML105' emerged on the first day of each month was also simulated (Fig. 5.4). The model

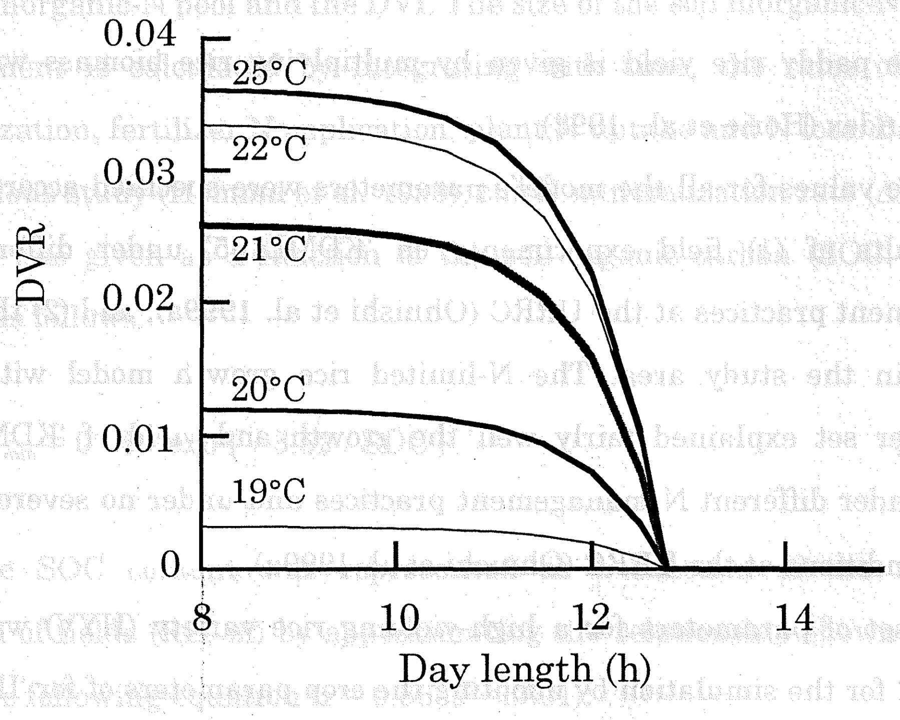


Fig. 5. 3. The response curves for the developmental rate (DVR) of rice cultivar KDML105 to day length and temperature, from seedling emergence (DVI=0.0) to panicle initiation (DVI=1.0).

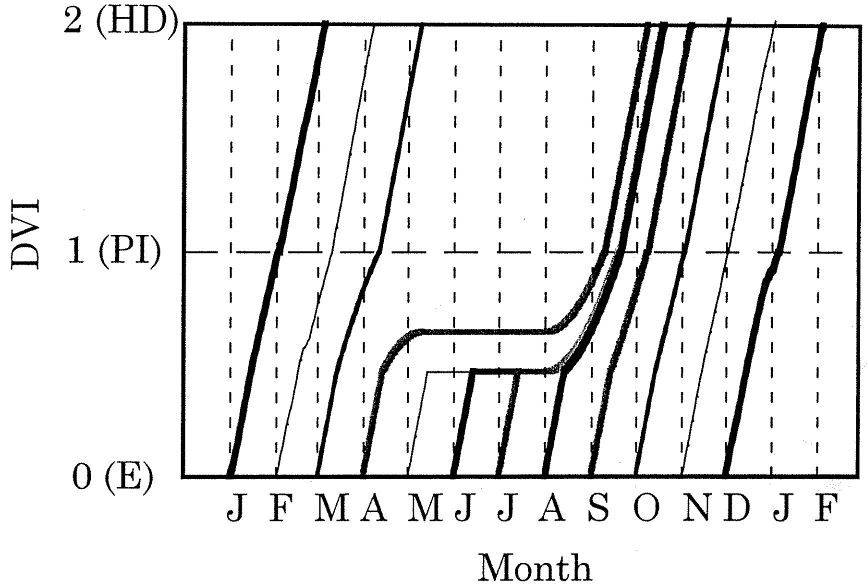


Fig. 5. 4. Simulated time courses of the developmental index (DVI) for rice cultivar KDML105 according to the month of emergence (E), Ubon Province, Northeast Thailand. PI: panicle initiation and HD: heading.

effectively simulates the commonly accepted phenomenon that all 'KDML105' crops seeded at any time during May–August attain heading at almost the same time in October.

Rice yields were simulated for all 247 fields in the Hua Don mini-watershed by taking into account farmers' actual transplanting dates and fertilizer application rates, and compared with measured yields (Fig. 5.5). The model overestimated the actual yields in the mini-watershed because the model did not account for yield loss to water stress, weeds, pests and diseases. Despite this, the model fairly well simulated the toposequential distribution of rice yield in the mini-watershed. The simulated yield average for higher fields was 1.65 t ha^{-1}, indicating that those fields have a very low production potential, even if no water stress existed. The poor yield potential of those fields is due not only to less fertilizer application and later

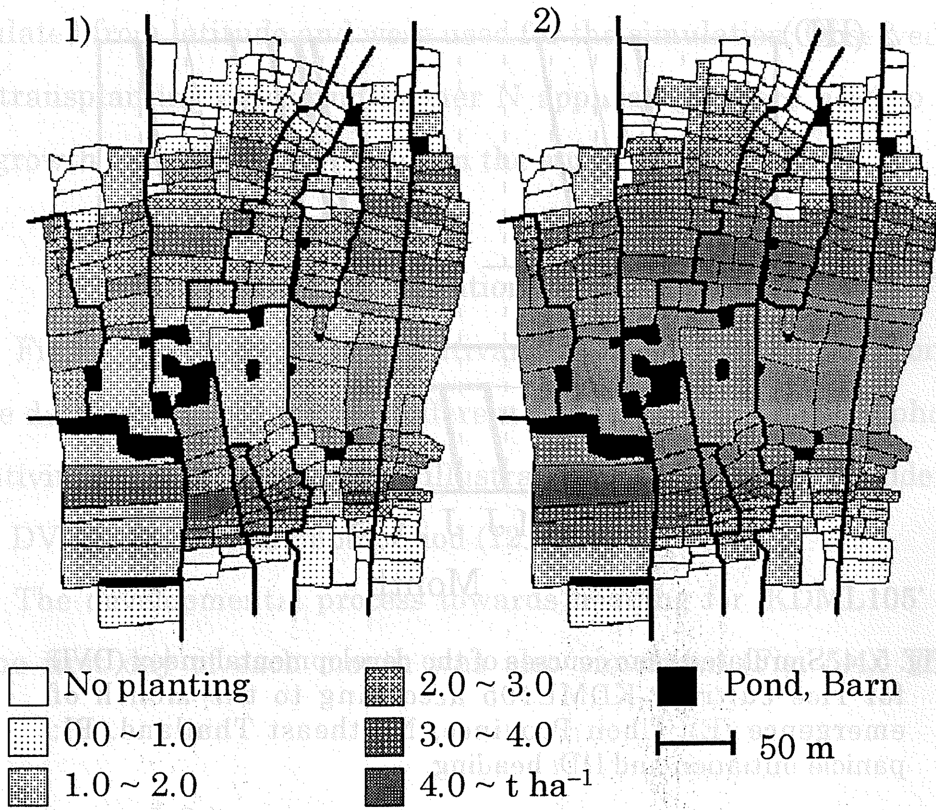


Fig. 5. 5a. Spatial distribution of observed (1) and simulated (2) rice yields at farmers' fields in the Hua Don study area in Northeast Thailand in 1998. The yield is given as paddy with 14 % moisture content.

transplanting, but also to very low SOC contents, as described in Chapter 1 and 3.

Effects of rice genotypes, N applications and transplanting dates on the average yield over 247 fields in the mini-watershed were simulated by the model (Fig. 5.6). The simulated yields for 'KDML105' linearly declined with the delay in transplanting date and showed a weak response to applied N, which agreed well with observations. The HYV showed no yield response to transplanting date because of its photoperiod insensitivity. The HYV showed higher response to applied N than did 'KDML105' because it has a larger

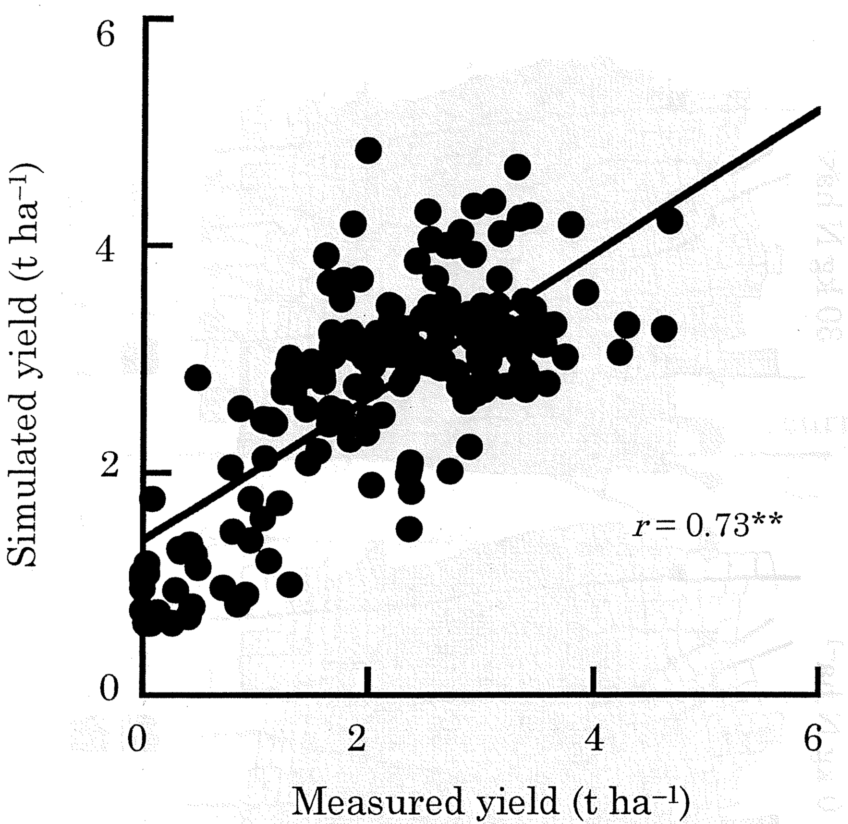


Fig. 5. 5b. Comparison between observed and simulated rice yields of farm fields in the Hua Don study area, Northeast Thailand, 1998. Yield is given as paddy with 14 % moisture content.

harvest index. The superiority of the HYV in this region was evident only at the latest transplanting (16 August) and with a N application of more than 60 kg ha^{-1}. Otherwise, the yield of 'KDML105' exceeded that of the HYV.

These simulation results agree well with the experimental results obtained at the URRC (Ohnishi et al. 1999b), suggesting, therefore, that later maturing genotypes such as 'KDML105' are better adapted to the very poor soil fertility conditions of Northeast Thailand, because they can accumulate more N over their longer growing period.

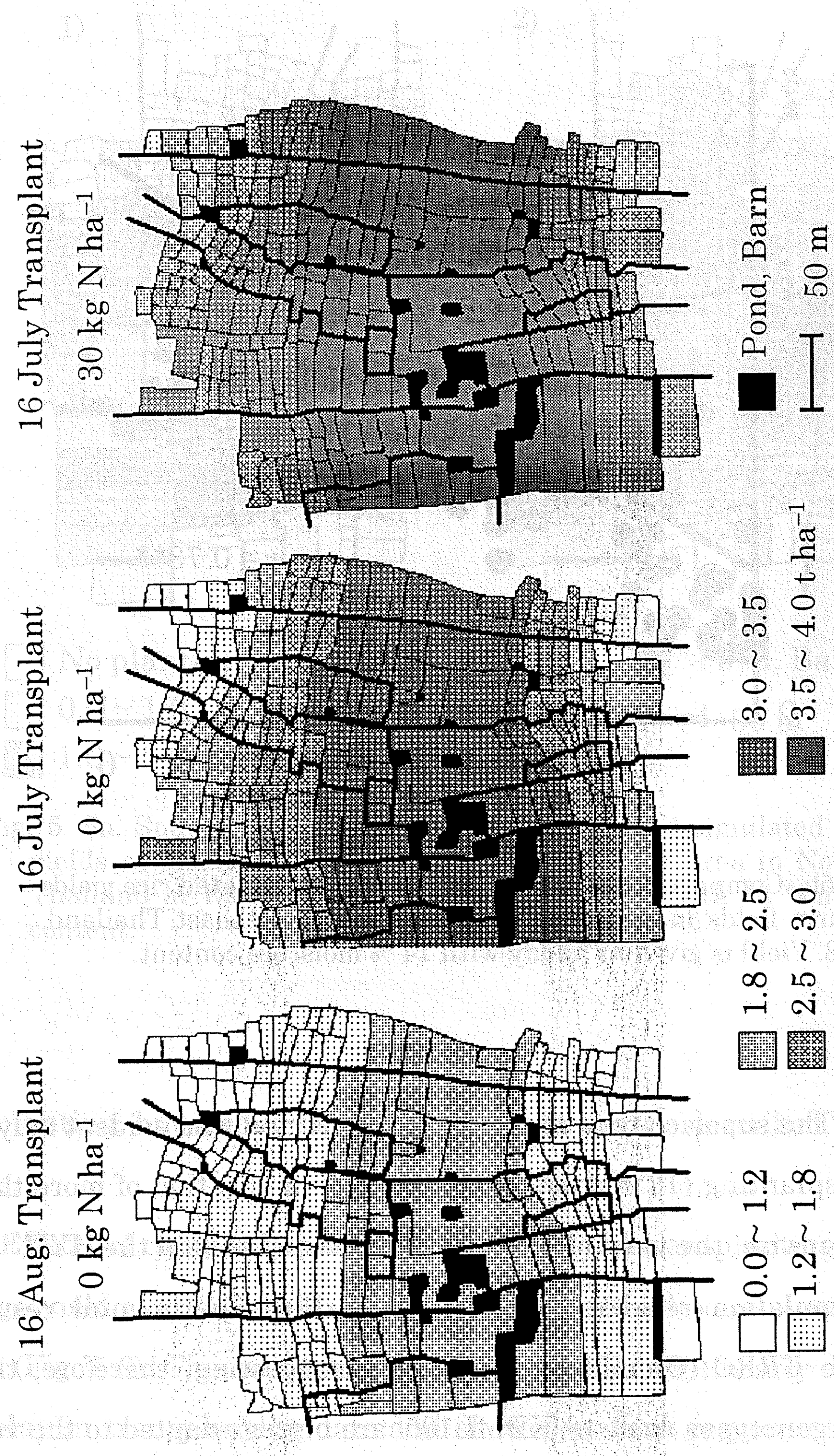


Fig. 5. 6a. Spatial distribution of paddy yield in the Hua Don study area, Northeast Thailand. Simulated for cultivar KDML 105 transplanted at different day and grown under different N managements.

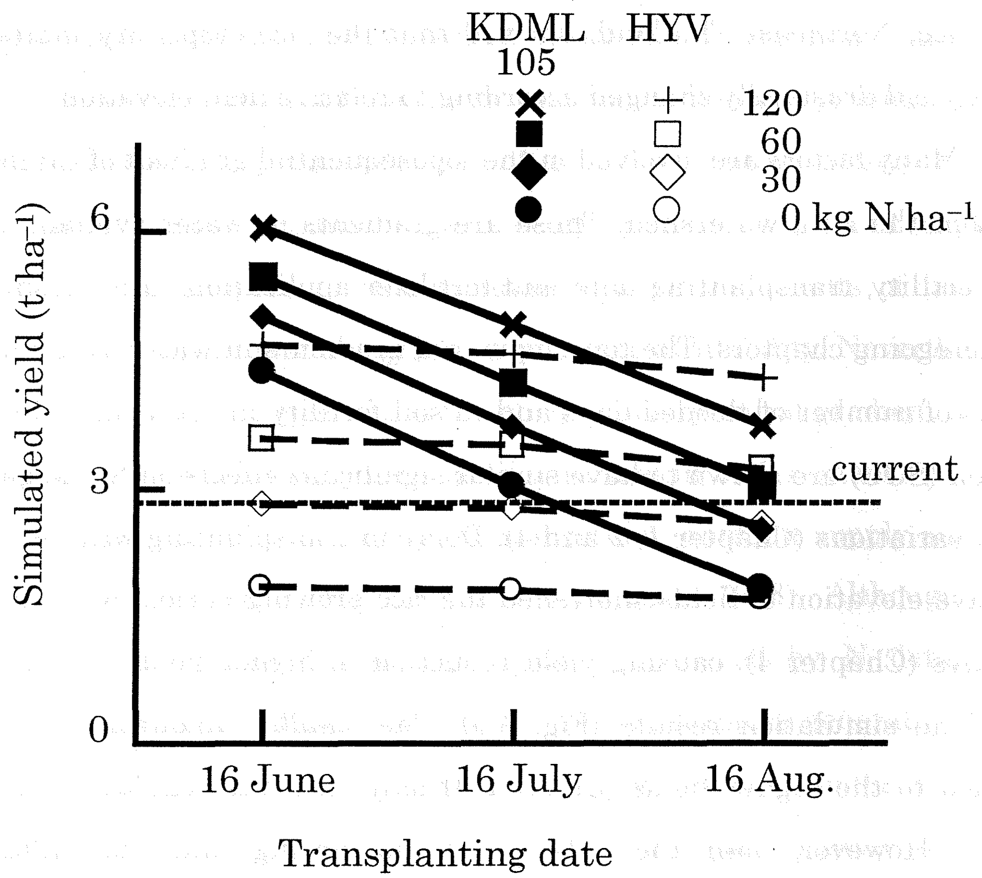


Fig. 5. 6b. Simulated responses to transplanting date and fertilizer nitrogen (N) application for yields of rice cultivar KDML105 and a high yielding variety (HYV), averaged over 247 fields in the Hua Don study area, Northeast Thailand. For the HYV, crop parameters for rice cultivar IR64 were adapted. The line designated as 'current' indicates the simulated average yields for the current cultivar, transplanting dates and N applications practiced in this area.

Discussion

Wade et al. (1999b) suggested the existence of toposequential variation in rainfed rice yields within small areas, a phenomenon that is also well known to farmers. However, the data that explicitly showed this were very few. Miyagawa and Kuroda (1988) reported that rice yields in a village differed according to toposequence in a drought year, but not significantly so in a bumper year. This study, conducted in a mini-watershed located in Ubon Province, Northeast Thailand, showed that the rice crop's dry matter and grain yield drastically changed according to relative field elevation.

Many factors are involved in the toposequential gradient of rainfed rice yield in the mini-watershed. These are gradients in water availability and soil fertility, transplanting date and fertilizer application rate, as shown in the foregoing chapters. The toposequential gradients in water availability in terms of number of flooded days and in soil fertility in terms of soil organic carbon (SOC) are shown to have similar significant effects on toposequential yield variations (Chapter 1, 2 and 4). Delay in transplanting with ascending relative elevation of fields shortened the rice-growing period by as many as 16 days (Chapter 4), causing yield reduction in higher fields, as suggested from the simulation results (Fig. 5.6). The smaller amounts of fertilizer applied to the higher fields (Chapter 4) may also have caused their lower yields. However, both the delay in transplanting and the differential fertilizer application for different fields are associated with the farmers' adaptation to the toposequential gradient in water availability in the fields. Therefore, the toposequential gradients in water availability and SOC content are considered to be primary factors in the steep gradient for yield.

The effect of SOC content on the toposequential yield variation was examined, using the N-limited rice growth model. This model was developed according to the concept that biomass production of potted rice was proportional to SOC content under irrigated conditions (Chapter 1) and on the results of a previous study by Homma et al. (1999) that the N-mineralization rate of soils was closely related to SOC content (see Chapter 3).

Rice yields of 247 fields were simulated by the model, using actual transplanting dates and fertilizer application rates for each field. Even though the current model does not explicitly account for the water factor, it explained fairly well the observed yield variability in the mini-watershed (Fig. 5.5). However, this does not mean that toposequential gradient of the mini-watershed's rice production potential is determined mostly by the gradient in SOC alone, because the actual transplanting dates and fertilizer application rates adopted for the simulation were the results of farmers adapting to the toposequential gradient in water availability. Nevertheless, the simulation results suggest that the steep toposequential gradient in the yield of rainfed rice is strongly associated with that in SOC content.

Soil organic matter has many roles, including nutrient supply and soil structure improvement (Hamblin 1985; Jenkinson 1988). Although rice production in Northeast Thailand is mostly restricted by N deficiency (Nakamura and Matoh 1996; Wade et al. 1999a), farmers generally apply only small amounts of chemical N fertilizer (also see Chapter 4). This suggests that N derived from the decomposition of organic matter plays an important role in these poor soils, and that SOC content is a good index for soil fertility. Willett (1995) reported that organic matter is also important for increasing the cation-exchange capacity of the sandy soils in Northeast Thailand.

Many studies report that soil fertility declines with time after forest is cleared for paddy fields in the tropics (Greenland and Lal 1977; Oldeman et al. 1991). Our study showed a loss of SOC content in higher fields through deforestation and its accumulation in the lower fields (Chapter 1). Soil moisture, clay contents and amount of incorporated organic matter also affect SOC content. In this study, whether SOC content is declining or is being maintained could not be judged from the data obtained.

In Northeast Thailand, except for some farmyard manure, rice residues form the only source of organic matter for the fields. Previous studies showed that soil fertility increased with the incorporation of rice straw (Chairoj et al. 1996; Naklang et al. 1999). Rice residues may therefore comprise one key to sustainable production under the current situation of rainfed-rice farming in Northeast Thailand. Introducing high-yielding rice varieties (HYV) with higher harvest indexes may not effectively improve the productivity of rainfed rice under the current situation, but it may also reduce sustainability because of the small quantities rice straw and other residues being incorporated.

Summary

In order to develop strategies for improving the productivity and sustainability of rainfed-rice cultivation, the toposequential distribution of land productivity with in the Hua Don mini-watershed was quantified by using a simulation model based on soil fertility. The model simulated fairly well the observed toposequential distribution of rice yields for the 247 fields, indicating that increasing soil organic carbon (SOC) in higher fields in key to improving productivity. The simulation also suggested that, under the current situation of rainfed lowland rice cultivation in Northeast Thailand, the rice cultivar KDML 105 would have higher yields than would a modern variety with shorter growth duration and higher harvest index.
Keyword: cultivar; farmers' management; fertilizer application rate; model simulation; soil fertility; transplanting; yield variability;

General Discussion and Conclusions

This study analyzed rainfed rice productivity in Northeast Thailand based on toposequential variation in environmental resources, soil fertility and water availability, in mini-watersheds and farmers' crop and land managements. The environmental resources drastically changed according to the relative field elevation, producing quite large difference in biomass production and yield of rice. Farmers' managements were fairly well adapted to the toposequential distribution of soil fertility and water availability. Difference of managements among farmers was generally small except for amount of applied chemical fertilizer. Farmers who applied more amount of fertilizer tended to have better grain yield. The simulation results suggest introduction of high yielding variety gains rather small benefit, while earlier transplanting of current cultivar does large.

The existence of toposequential variation in soil fertility and water availability in Northeast Thailand was reported in previous studies (Fukui, 1993; Craig and Pisone, 1988). However, these studies classified paddy fields only into upper, middle and lower, and stated literarily the difference among them in the environmental resources. Such classifications may help conceptual understanding of rainfed rice production, but provide limited information for analyzing rice productivity. The soil fertility evaluation by using phytometer with rice as test plant, and monitoring field water conditions employed in this study provided their continuous distribution data along with toposequence in mini-watersheds (Chapter 1 and 2). The analysis of rice growth and yield based on the toposequential distribution of the environmental resources revealed that biomass production of rice was mainly restricted by soil fertility, and that water availability affect rice yield via harvest index (Chapter 3).

Water availability was simply affected by precipitation and the relative field elevation, while soil fertility complicatedly determined. As shown in Chapter 1, the soil fertility evaluated by the phytometer experiment with potted rice was strongly related to soil organic carbon (SOC). SOC is probably important as a source of nitrogen (N) in poor fertile soil there. Field toposequence affects soil fertility through soil erosion and nutrient leaching, which make lower fields more fertile. Toposequential variation in water availability may also affect soil fertility through decomposition rate of SOC. The decomposition rate is known to be strongly influenced by soil moisture content during dry season (Birch, 1958; Van Veen et al., 1985). The most important source of organic matter in rainfed lowland in Northeast Thailand is rice residue except for small amount of farmyard manure. Rice straw management after harvest is one of the key factors for sustainability of soil fertility, as previous studies insisted (Chairoj et al., 1996; Naklang et al., 1999).

Timing of transplanting and fertilizer application varied depending on standing water conditions (Chapter 4; also see Miyagawa, 1995). Water shortage from June to August delays transplanting and then fertilizer application, and sometimes suspends these activities. Farmers decide amount of chemical fertilizer application by field observations of rice growth and also by financial conditions of households (Nakada, 1996; Funahashi, 1996; also author's interviews to farmers). These farmers' managements and environmental factors affect rainfed rice productivity in Northeast Thailand, as schematically presented in Fig. 6.1.

Strategies for improving rice productivity there must be developed under such conditions. It was simulated that yield increase was relatively small under current soil fertility and farmers' managements, even if water was sufficient (Chapter 5). Investigation in 1980s reported that farmers in

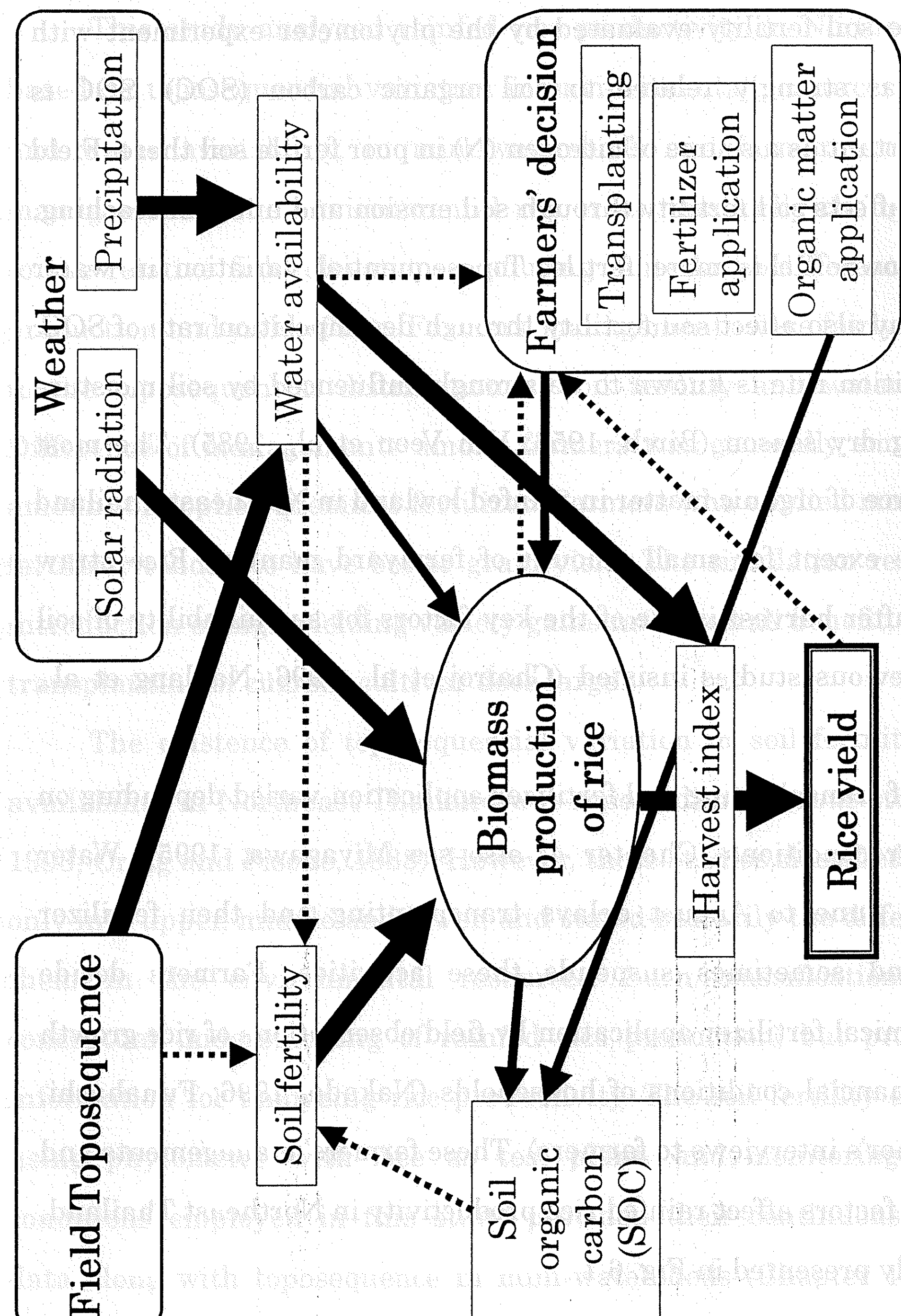


Fig. 6.1. Schematic model representing major processes and factors by which rainfed lowland rice yield is determined in mini-watersheds in Northeast Thailand.

Northeast Thailand planted tens of cultivars, those of early-maturing at upper fields and those of late-maturing at lower (Fukui, 1992; Craig and Pisone, 1988). Exclusive planting of two cultivars, KDML 105 and RD 6, at the present means reduction of adaptability to toposequential variation in the water availability, but average rice yield in Northeast Thailand increased from 1980s (OAE, 1980-2000). Introduction of chemical fertilizer explains the yield increase, rather than higher productivity of these two cultivars than old cultivars (Miyagawa, 1996). The fact also suggests that improvement of soil fertility and farmers' managements are more important than that of water availability under the current conditions.

The problem associated with increasing the soil fertility is how farmers secure organic matter for incorporation. Previous studies insisted on green manure and legume intercropping for source of organic matter (Pandey, 1991; Wade and Ladha, 1995; Hererra et al., 1996; Supapoj et al., 1998), but these methods seem not yet practical for farmers, or it seems necessary to make farmers turn their eyes to importance of land managements. Unless the problem in the security of soil organic matter is solved, introduction of a semi-dwarf high yielding cultivar, which produces fewer residues with higher harvest index, may reduce sustainability of rice production in this area.

Longer growth duration with earlier transplanting is one of the keys for increasing rice yield under such low soil fertility (Chapter 5). Strong photoperiod-sensitivity as current cultivars have is still necessary at fields where rice plant don't suffer sever water stress. Such fields occupied more than half of planted area according to the evaluation by the heading date as water stress index (Chapter 2). Direct seeding also extends growth duration at paddy fields then increases rice yield (Naklang et al., 1996; Fukai et al., 1998). Since weed and submergence are the problems for direct seeding, sowing before flooding (early in May) at lower fields seems adaptable to the current conditions (also see Konchan and Kono, 1996).

Experimental results showed that KDML 105 attained the maximum yield of 4 t ha^{-1} with total biomass of 10 t ha^{-1}, and more biomass production led to less yield because of lodging (Romyen et al, 1998; Ohnishi et al., 1999b). Fig. 5.6 indicates that transplanting on 16 June was able to produce a yield of 4 t ha^{-1} with no fertilizer application, and that similar yield could be obtained by 16 July transplanting with 30 ~ 60 kg N fertilization to the fields in the mini-watershed. The current managements are still behind to obtain the maximum yield level, and only limited fields attained the maximum (Chapter 4). Optimum amount of chemical fertilizer must be reconsidered at upper fields where severe drought is developed. Although it is said that fertilizer application increases resource capture ability, severe drought may reduces rice yield to almost zero via reduction of harvest index (Fig. 2.7).

Higher adaptability to low soil fertility is necessary for new cultivars, but the adaptability doesn't simply means more yield productivity. Recent improvement in the yield has been achieved by increase in the harvest index (Evans, 1999), having the risk of reducing soil fertility as above mentioned. Improvement in nutrients use efficiency for biomass production is preferable under the conditions of Northeast Thailand. However, slight increase in the nutrients use efficiency doesn't expect so much improvement, because the absolute quantity of nutrients is quite limited. For breeding rice genotypes with higher adaptability to the rainfed condition, more effort seems to be necessary.

Quite low soil fertility at uppermost fields is generally accompanied with quite severe water shortage (Chapter 1 and 2). Since substantial rice yield can hardly be obtained at such fields, conversion from rice cropping to green manure or forage crops at uppermost fields is one of choices for the productivity improvement as a whole mini-watershed. Introduction of green manure or forage crops at uppermost fields, or feeding them to livestock can provide organic matter for the rest of the fields. The organic matter application probably compensates yield loss caused by the conversion, besides may improve sustainability and stability of rice production of the whole mini-watershed. Such land and crop managements and breeding of more adaptive genotypes by taking into account the toposequential variability of the environmental resources are necessary for sustainable development of rainfed lowland rice production in Northeast Thailand.

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和文要旨

Quantifying the Toposequential Distribution of Environmental Resources and Its Relationship with Rice Productivity in Rainfed Lowland in Northeast Thailand

（東北タイ天水田地域における環境資源とイネ生産力の地形連鎖分布の量的解析）

本間　香貴

天水田は世界の稲作面積の３分の１を占め、生産性が低くかつ不安定である。今後の食糧安全保障を考えるに当たり、こうした地域における生産性の向上が必要とされる。代表的な天水田地域である東北タイは、頻発する干害と貧弱な土壌により水稲収量が約 1.7 t ha^{-1} と非常に低い。水稲生産性を改善するために、品種や栽培方法の面から様々な研究や取り組みが行われてきているが、収量は依然として低いままである。

本研究は、東北タイの地形の構成単位であるノングと呼ばれる広さ数 km^2 深さ数ｍの窪地に着目し、そこでのイネ生産性を支配する要因と機構を明らかにし、生産性改善の可能性を探ろうとするものである。そのためにまずノング内の農家圃場における環境資源（土壌肥沃度と水）の変異を調査し、環境資源の地形連鎖分布がイネの生育・収量に与える影響を調査した。また農家の栽培管理が水稲収量に与える影響についても調査を行い、ノングにおける環境資源の分析と栽培管理が天水田水稲の生産性に及ぼす影響を、最終的にシミュレーションモデルを用いて評価した。

第１章　土壌肥沃度の分布

東北タイの土壌は砂質であるため肥沃度並びに養分保持力が低く、また水田間で大きな変異を示すと言われている。ここでは農家水田から採取した土壌を用いて、イネをポット栽培することにより土壌肥沃度の評価を行い、そのノング内における分布を調査した。ポット栽培水稲の乾物生産量によって表される土壌肥沃度は、土壌によって５倍もの差異が見られ、その差異は土壌有機炭素含量(SOC)のそれと密接に関係していた。SOC は地形連鎖変異を示し、圃場の相対標高が高くなるにつれて低くなった。土壌の粘土含量も同様に相対標高にしたがった変化を示し、隣接する二次林の土壌分析結果から水田化による SOC と粘土の流出が示唆された。

第２章　水条件の変異

一般に天水田では水ストレスが卓越すると言われている。そこでノング内の圃場の水条件（湛水日数と土壌水分含量）分布がイネにどのような水ストレスを与えているかを明らかにしようとした。イネは水ストレスによって出穂が遅延すること、および現地で栽培されている水稲品種 KDML105 と RD6 はいずれも強い感光性を持ち、水ストレスがない場合通常の作期（５～８月）の移植では出穂日はほぼ一定になることから、出穂日の遅延を水ストレスの指標とした。湛水日数と土壌水分含量は地形連鎖分布を示し、相対標高の高い水田では全く湛水が得られず、土壌水分も極めて低かった。イネの出穂日は生育期の土壌水分含量と強い相関があり、出穂の遅れは積算水ストレスを示すとする研究結果を裏付けた。またイネの出穂日から判断すると、最上位に位置する水田では厳しい水ストレスが生じている一方で、ほとんど水ストレスが発生しない水田が調査地域の半分以上の面積を占めることがわかった。

第３章　乾物生産の地形連鎖分布

ノングにおけるイネの乾物生産の変異を、イネの窒素吸収量の面から解析した。環境資源（土壌肥沃度・水）の地形連鎖分布にしたがい、水稲の乾物生産は下位田で 10 t ha^{-1} 以上、上位田で 4 t ha^{-1} 以下と変化した。乾物生産量はイネの窒素吸収量と強い相関があり、この窒素吸収量は土壌肥沃度の指標である SOC と密接に関係していた。水ストレスの窒素吸収に及ぼす影響は比較的小さかったが、一方で水ストレスは収穫指数に大きな影響を与えており、SOC が乏しくまた水ストレスの強い上位田ではほとんど収穫が得られなかった。

第４章　栽培管理の収量への影響

調査地域において、農家の栽培管理が水稲収量に与える影響を調査した。農家の栽培管理のうち水稲移植日と施肥量は、環境資源の地形連鎖分布に比較的よく適応しており、移植は下位田から上位田へと行われ、施肥は中位田で多く上位田で少なかった。施肥量は概して少なかったため、環境資源の地形連鎖分布と移植日の影響により、相対標高が上がるにつれて収量は減少した。栽培管理の農家間における差異は、施肥量において顕著であり、この差異が農家間の収量差をもたらしていた。その他の雑草や水管理には、農家間や相対標高による差異は見受けられなかった。

第５章　シミュレーションモデルによる評価

天水田水稲の生育・収量を評価するシミュレーションモデル構築の第一段階として、まず土壌肥沃度と栽培管理（品種・移植日・施肥量）が収量に及ぼす影響を評価するモデルを構築した。シミュレーション結果は実収量の地形連鎖分布を比較的よく再現しており、モデルの妥当性が示された。シミュレーションにより、現行の栽培管理のままではたとえ水が豊富に得られたとしても収量が低いままであることが示された。土壌肥沃度が低いため、生育期間の短く収穫指数の高い近代的な多収品種は、多肥晩期栽培の場合でのみ現行品種に比べ優位性を保つが、概して利点が少ないことが判明した。現行品種を用いる場合，早期移植により長い生育期間を確保することが重要である。

このようにノング内の農家天水田圃場において，環境資源（土壌肥沃度・水）は大きな地形連鎖変異を示し，それがイネ生産性を決定していることが明らかになった。ノング全体で見ると，水資源の影響は比較的小さく，生産性向上のためには土壌肥沃度の改善が必要不可欠であることが示された。土壌肥沃度は有機物の投入により改善するが，東北タイではこの投入有機物の確保が問題である。現在の状況では水稲の収穫後残差がほぼ唯一の有機物源であるため，この問題を解決せずにわら生産量が少ない高収量性品種を導入することは，生産持続性を減ずることになりかねない。最上位に位置する水田では土壌の劣化が激しく、生産技術の改善によってもそれに見合う収量は期待しがたいので、緑肥や飼料生産の場とし，ここでの産物を他の水田に投入し，全体としてイネ生産性と生産持続性を高めることも選択肢として考慮すべきである。このような水稲生産性の地形連鎖分布を考慮して、新品種の開発および作物・土地管理方法の改善が，この地域の水稲の生産性向上と安定化に必要である。